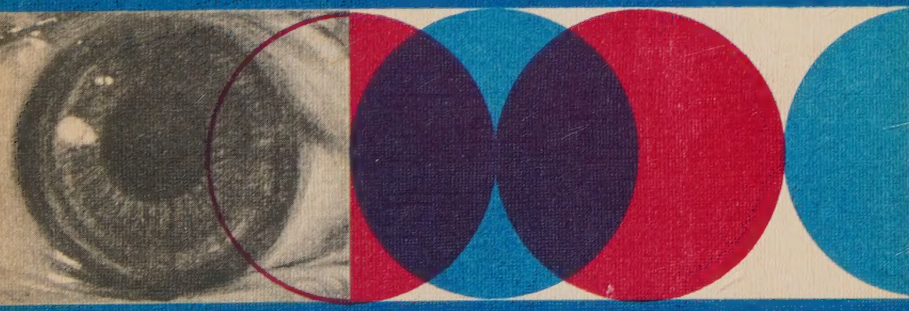
The Human Eye and the Sun

'Hot' and 'Cold' Light

S.I. VAVILOV
Formerly President of the U.S.S.R. Academy of Sciences



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THE HUMAN EYE AND THE SUN

"HOT" AND "COLD" LIGHT

THE HUMAN EYE AND THE SUN

"HOT" AND "COLD" LIGHT

by S. I. VAVILOV

Translated from the Russian by
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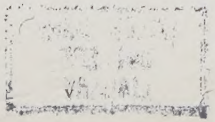
In this translation I have been most conscious of the author's eminence and his mastery over words. In the belief that a classic piece of literature is outstanding by its fitness for a particular object in the most pleasing form, I have sought to re-express the author's ideas in terms which would best further the interest in science of English-speaking persons with no formal scientific training.

I have translated the book at its face value, though conscious that the supreme art may be the concealment of art. Popularization of science may of course pursue a variety of aims, but not least of these is its romance, and it is this which perhaps stands out most clearly in my modest interpretation.



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THE HUMAN EYE AND THE SUN

Light, the Sun and Energy

FOREWORD

This booklet by S. I. Vavilov *The Human Eye and the Sun* was first published in 1927. Later editions appeared in 1932, 1938, 1941, 1950, 1956 and 1957. This edition is reproduced from the text of Volume IV of the works of the late president of the U.S.S.R. Academy of Sciences, S. I. Vavilov (U.S.S.R. Science Academy Publishing House). *The Human Eye and the Sun* (jointly with the book *The Microstructure of Light*) was awarded a Stalin Prize First Class in 1951.

INTRODUCTION

War nicht das Auge sonnenhaft,
Wie könnten wir das Licht erblicken?
Unless our eyes had something of the sun,
How could we ever look upon the light?*
Goethe

Comparisons have been made between the eye and the sun since time immemorial. These comparisons have not come from science. Poetry, whether intentionally or unintentionally, still draws upon the phantasies of children and primitive man and lives side by side with the progress of modern natural science. It is often rewarding to take a peep into this other world as a source of new scientific hypotheses. It is a wondrous story-book world, but connexions between natural phenomena are found which to scientists seem unrelated. In some cases these bridge relationships are guessed correctly, in others they may be radically mistaken, or simply absurd, but they always deserve attention because they often help in the pursuit of truth. For this reason it will be instructive to approach the relationship between the eye and the sun from the standpoint of the child, primitive man, and the poets.

When playing hide-and-seek, children frequently hide themselves in the most astonishing manner. They screw up their eyes or cover them with their hands and pretend that they cannot be seen. For them, vision is instinctively identified with light.

It is not surprising to find a similar confusion of vision and light amongst adults. Photographers, experienced though they are in practical optics, often catch themselves closing their eyes when they have to be particularly careful in keeping the light out of the dark-room when loading or developing films. Instances of the same fallacy occur in our everyday speech. People talk quite obliviously of "sparkling eyes", "the sun peeping out" and "stars looking down".

* Translation by F. N. Stawell and N. Purtscher-Wydenbruck.

It is usual, one might even say essential, for poets to ascribe the properties of vision to celestial bodies and imagine that the eyes radiate light:

> The stars of night
> Look down like keen accusing eyes,
> And haunt him with their mocking glance.
> . . . His eyes dart fire . . .
>
> *Pushkin*

> With you we gazed upon the stars,
> And they on us.
>
> *A. A. Shenshin* (1820–1892)

> The all-seeing sun
> Ne'er saw her match since first the world begun.
> Romeo and Juliet I, 2.97
>
> *Shakespeare*

Rays of light, regarded as attributes of vision, have been likened to eyelashes:

> Scintillate the golden lashes of the stars.
>
> *A. A. Shenshin*

Many such examples are to be found in the works of the ancient poets as well.

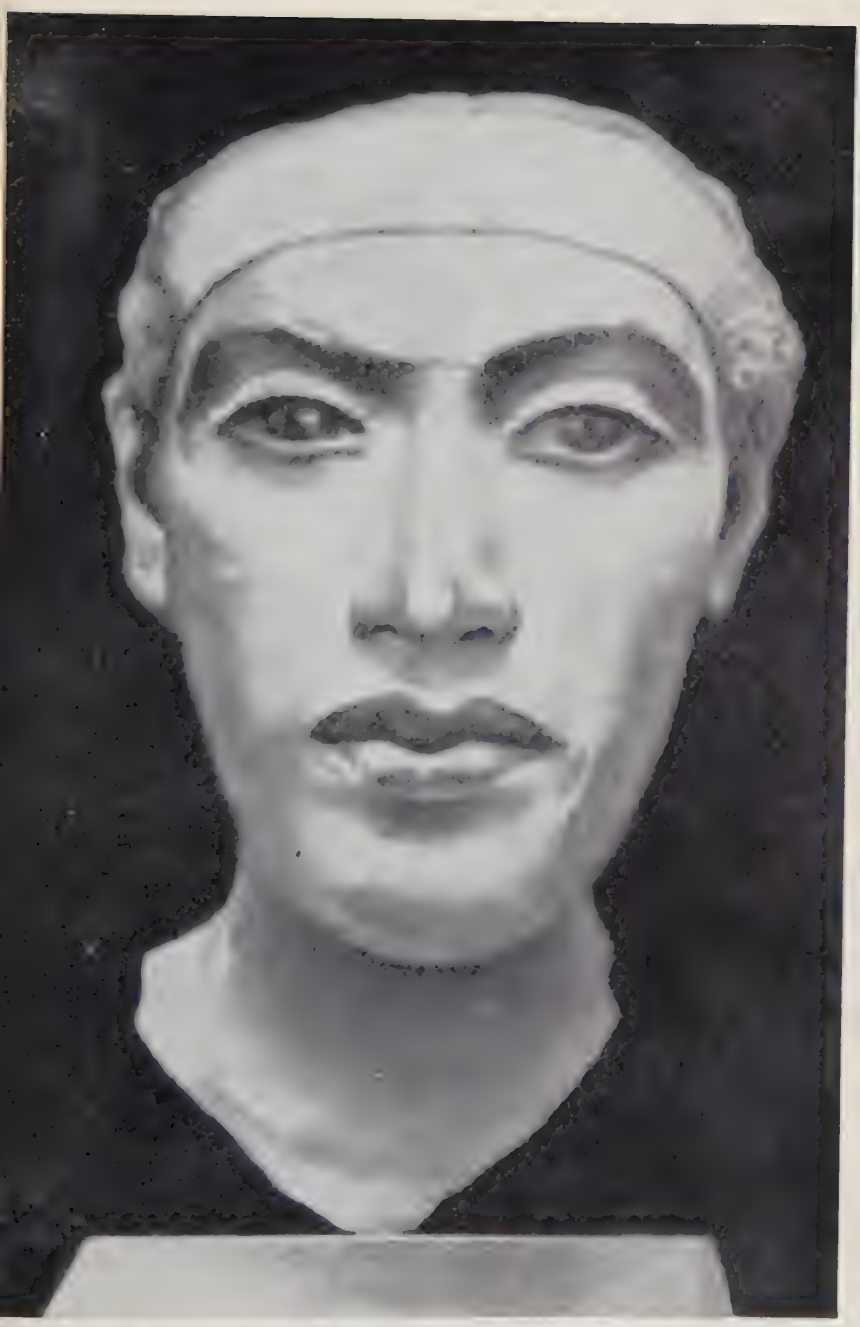
The relationship between the eye and the sun runs right through ancient Egyptian mythology, ritual and hymns:

> How beautiful both eyes of Åmen-Ra,

says a Theban hymn, meaning by the eyes of the deity the sun and the moon. Other lines of the same hymn reveal the intricate interlacing of the notions of light and vision:

> Men began to see
> When thy right eye first blazed
> And thy left banished the gloom of night.

A later ancient Egyptian image "the all-seeing eye" has the form of an eye surrounded by rays (Fig. 1). Here the eye sees and shines at the same time. The eye and the sun, vision and light, are fused into a single entity.



AMEN-HETEP IV, founder of the cult of the real sun in

This was the fundamental, though unconscious, theory of pre-scientific and primitive optics. There is, however, another aspect of ancient beliefs which requires our attention.

FIG. 1. Sculptural image of the "all-seeing eye" on the pediment of the Lyceum Church, Town of Pushkin.

We continually talk about light "cutting through", "striking", "breaking through" and "flowing". Indeed, the term "light flux" has been adopted in modern scientific and technical writing. The poets also liken light to a liquid.

> The gold of His rays to the Pharaoh's nostrils streams.
> May I be bathed daily in Thy beams!
>
> Ancient Egyptian Hymn

> Again with avid eyes
> The life-giving light I drink.
> . . . Lightning-like spurts the beam
>
> *Tyutchev*
> Russian poet (1803–1873)

> And sprinkles the sun in handfuls
> Its rain all over me.
>
> *Esenin* (1895–1925)

At times this association of light with corporeal objects and fluids takes a definite form. For instance, in ancient Egyptian sun-worship at the time of Amen-heter IV (1350 B.C.), the rays of the sun-disk Aten are tipped with fingers (Fig. 2). In the Russian, the word *luch*

FIG. 2. Egyptian image of real sun worship from El-Amarna. Period of Amen-heter IV.

for "ray" has the same root as the word *luk* for "arrow". The same association of light and matter is sometimes evident in our own instinctive behaviour. M. Gorky in his reminiscences relates "I saw Chekhov sitting in the garden catching sunbeams in his hat and trying in vain to tip them on his head". Catching sunshine by one's hat is hardly less odd than the sun hands of Àten.

This persistent association of light with moving substances and fluids by poets, by primitive men and in our own instinctive behaviour is indicative of a natural subconscious association, whereas the identification of light with vision springs from our confusion of the external world with our own sensations. This confusion is very strong in children and primitive people though to some extent it still persists amongst civilized men in their unguarded moments. The triumph of materialistic science has above all been the distinct separation of subjective feelings from the external world.

Consciousness prevails and smashes the delicate lattice-work of childish and poetical optics. Gradually the child distinguishes between feeling and fact, dreams and reality, illusion and life. Pushkin, the celebrated Russian poet, naturally knew that the stars did not haunt and mock. Shenshin knew that they could not gaze. Chekhov did not need to be told that sunbeams cannot be caught in a hat.

Throughout the world the alluring phantasies of children have been a fount of inspiration for poets. The optics of children and poets will survive in everyday life and poetry for ages to come. It now exists alongside of consciousness and science, but in the past it has not always been separate.

In this respect the history of the science of light is a particularly good illustration. It began with attempts to transfer the "optics of children and poets" into the province of conscious progressive thought. The two main "theories" which were evolved identified light with vision and regarded light as matter. These were the cornerstones of the study of light in ancient Greece and they remained so in different forms until almost the seventeenth century A.D.

In the famous natural science dialogue "Timaeus", Plato writes*:

> "And of the organs they (the Gods) constructed first light-bearing eyes, and these they fixed in the face for the reason following. They contrived that all such fires as had the property not of burning but of giving a mild light

* Bury's translation, Loeb ed., pp. 102–103.

should form a body akin to the light of every day.* For they caused the pure fire within us, which is akin to that of day, to flow through the eyes in a pure and dense stream; and they compressed the whole substance, and especially the centre, of the eyes, so that they occluded all other fire that was coarser and allowed only this pure kind of fire to filter through. So whenever the stream of vision is surrounded by mid-day light, it flows out like unto like,† and coalescing therewith it forms one kindred substance along the path of the eyes' vision, wheresoever the fire which streams from within collides with an obstructing object without. And this substance having all become similar in its properties because of its similar nature, distributes the motions of every object it touches, or whereby it is touched throughout all the body even unto the Soul, and brings about that sensation which we now term 'seeing'. But when the kindred fire vanishes into night, the inner fire is cut off; for when it issues forth into what is dissimilar it becomes altered in itself and is quenched, seeing that it is no longer of like nature with the adjoining air, since that air is devoid of fire."

Thus, in Plato, the mild light of the eyes corresponds to the kindred fire of the sun and the closing of the eyes for the night, to the setting of the sun.

Damianos Heliodorus of Larissa (fourth century A.D.) tried to defend the theory of ocular beams on the grounds that the eyes are not hollow with an aperture like our other sense organs and so cannot receive light, but being spherical in shape, they are adapted to emitting rays. That these rays were light rays was evident from the way that other people's eyes seem so bright at times and the fact that animals' eyes glow at night.

The great ancient mathematicians Euclid, Ptolemy and others used the theory of ocular beams to form a theory of light reflection by plane and spherical mirrors and founded the science of geometrical optics which has retained its significance to our day.

It is natural to inquire how the exceptionally high level of science, geometry, astronomy, mechanics and other fields of knowledge in ancient Greece can be reconciled with the absurdity of the theory of ocular beams as expounded by men such as Euclid and Ptolemy who left immortal works in geometry and astronomy.

Our perplexity is due to a loss of historical perspective. The principal, and at the same time, the most difficult problem confronting the ancients was to explain how the *image* of an object was formed. At

* There is a play here on the words "*ημερον*" ("mild") . . . ("*ημ'ερα ξ*") ("day") cf. Cratyl, 418c.

† Vision is explained on the principle that "like is known by like"; a fire-stream issuing from the eye meets a fire-stream coming from the object of vision (cf. the view of Empedocles).

that time they only knew of images which they could see for themselves, or could be drawn and painted. There were no other methods; even the simple camera-obscura was unknown, and the possibility of producing images on surfaces by lenses and concave mirrors was not even suspected. Moreover, the ancients were unfamiliar with the structure of the eye; the formation of images on the retina of the eye by the crystalline lens was unknown.

Under these circumstances vision, the faculty of registering images in the brain, seemed a singularly puzzling phenomenon. To the ancients the simplest solution was that the eye emitted ocular beams like feelers.

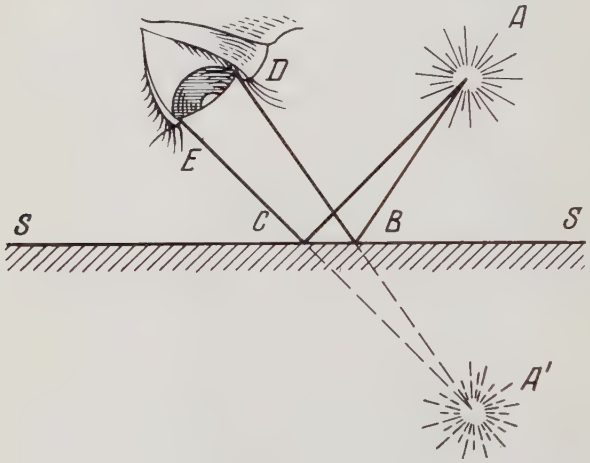


FIG. 3. Observing the reflection of a luminous point in a mirror.

Let us put ourselves in the same position as the ancients and consider the problem of how an image of a light point *A* is formed on a plane mirror *SS* (Fig. 3). The ancients knew of the rectilinearity of light propagation and the law of reflection. If they had known, as we know now, that the light proceeds from point *A*, they would have drawn the rays *ABD* and *ACE*. They would have found that the rays struck the eye at points *D* and *E*. But after that they did not know what happened to the rays and the existence of an image in the mirror at point *A'* was inexplicable, the more so as the rays diverge on approaching the eye as the diagram shows (Fig. 3). The idea of ocular beams, derived from the sacred images of primitive man and imagined

by children, came to the aid of the ancients in this seemingly insurmountable problem. Assume for a moment that the rays which create the image are in fact emitted by the eye and that somehow the eye senses the original direction of the rays radiating from it. In the example under consideration (Fig. 3), these ocular beams, like the light rays, are reflected at points *C* and *B* and they converge on the "source" at point *A*. The direction of the rays from the eye is, according to the ancients, somehow signalled to the brain and it seems that the rays do not meet after reflection, but at the imaginary point *A'* where the continuations of the original rays from the eye intersect. The advantage of this interception is that there is no need to know what happens to the light inside the eye. It is sufficient to assume that the original direction of the ocular beams is signalled in some way by means of the eye to produce the image in the brain. Despite its quaintness, this idea was undoubtedly useful and progressive in its day since it enabled a correct theory to be developed for the production of images by mirrors. It therefore survived for a very long time. Even Galileo resorted to it on occasion at the beginning of the seventeenth century.

The theory of ocular beams was only opposed in ancient times by the still more picturesque idea of Epicurus and Lucretius which involved "thin filmy images" of objects flying in all directions and striking the eye. According to Epicurus, and other ancient atomicists, very thin films are continually being separated from luminous and illuminated bodies which retain the same relief and features as the parent object. These replicas account for the picture produced in the eye. One might suppose that this idea would have "saved the situation", had not the geometrical optics of Euclid and Ptolemy been so perfect.

The theory of ocular beams has been considered at length in order to show that it was not a crude mistake on the part of the ancients, but the least of alternative evils.

For many centuries, from generation to generation, it was taught that the sun and the eye were brothers, that they were manifestations of the same kindred fire and that shining is seeing and seeing is shining. The earth was regarded as the centre of the world and man was the centre of that centre. The dividing line between poetic phantasy and science was indistinct, or it did not exist at all. Poetry encroached on science in an attempt to unite the two, but this unity was never stable.

Sometimes it was the other way round and consciousness and the

rudiments of objective science found their way into superstition and religion. For instance, in ancient Egypt, the relationship between the sun and the earth was originally that between a pagan god and primitive man. Their sacred image was a falcon, or a man with the head of a falcon, who sailed the heavenly ocean with the sun (Fig. 4). In an ancient Theban hymn:

> Åmen-Ra, the falcon deity,
> With his glittering feathers,
> Circles the heavens in one flap of his wings.

But in the fourteenth century B.C. a significant change came about. The new spirit of that time was undoubtedly the result of the observa-

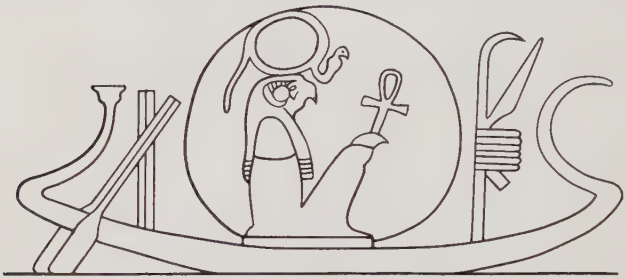


FIG. 4. Egyptian image of the pagan sun god in a boat.

tions and reflections of the Egyptian astronomers. History, however, has no record of their names and the stone hieroglyphs naturally ascribe the change to the Pharaoh. The Copernicus of ancient Egypt was thus Pharaoh Åmen-heter IV. A new cult of sun-worship was introduced during his reign. The real and true sun was worshipped, not the falcon and scarab. Pharaoh changed his name from Åmen-heter ("the beloved of Åmen") to Akh-en-Åten, which means the favoured of Åten, the sun disk. On monuments (see Fig. 2), their new deity is depicted simply as the sun with rays. The hymns to the real sun Åten no longer contained the colour, splendour and intricacy of the original sacred image, but glorified the blessings which the sun bestows. The great hymn to Åten by Ai, Overseer of the Horse to Akh-en-Åten, begins

> Thou shineth beautifully in the firmament,
> O Åten, alive and living since time began,
> When thou riseth in the East,

All lands are filled with thy beauty.
Light, great and brilliant,
High above all lands,
Thy rays embrace the lands
And all that thou has created on them

The sun was invoked as a superior entity and little was said about the brother-like equality between the eye and the sun. But with the passing of Akh-en-Áten the cult of real sun-worship disappeared in Egypt and thousands of years were to pass before science rose and freed itself from the arbitrariness of human feelings and instincts, rejecting the idea of man's privileged position in the universe ascribed to him by religion and ancient philosophy. Man came to regard himself as one of the phenomena of nature, as a product of the evolution of the living world on earth.

The ancients' belief that the eye is akin to the sun still persists in modern natural science, but in a profoundly different form. Modern science has discovered the true relationship between the eye and the sun. This relationship is quite different from that postulated by the ancients, or proclaimed by the poets. It is with this true relationship that the present book is concerned.

But, separated from science, though side by side with it, poets, and indeed all of us, will continue to speak of shining eyes and stars which watch over us, just as four centuries after Copernicus we still say that the sun rises and sets.

LIGHT

To what purpose have so many experiments been carried out in physics and chemistry, to what end the labours of so many great men and tests dangerous to life. Has it only been to stare and wonder at the disordered heap of things without pondering over their proper arrangement?

Lomonosov

The sun is about 92,500,000 miles from the earth; this distance is equivalent to a journey 4000 times round the earth. The light which is continuously bringing us news about the sun from such a distance, what is it, or more particularly, how can we distinguish it from the rest of our environment, what are its features? Until the seventeenth century the reply was that light is what the eye sees, the cause of visual perception. This property is clearly unsatisfactory as a distinguishing feature. In the first place, if one presses one's finger lightly against the eyeball near the nose in total darkness, queer bright spots appear. If light is to be called the cause of visual perception, resort must be had to the theory of ocular beams about which we spoke in the Introduction. Not every cause of visual perception can be called light. Secondly, it is necessary to ask whether all light is seen. Doubtless it is not. There is an infinite variety of phenomena which on consideration must be regarded as light, but which are in fact invisible.

Thus, in approaching the study of light, we meet with a serious difficulty in that the composition of the object of study is still unknown. To escape from this blind alley, let us consider our visual impressions a little more closely.

Visual images have two main qualities, *brightness* and *colour*. These are obvious qualities to all having eyes to see with and no explanations

are required*. But even brightness and colour are relative and selective. By day the moon is indistinguishable from cloud, but at night it has the status of the sun's deputy, "the other eye of Àmen-Ra". The stars, invisible by day, seem extremely bright against the background of the sky on a moonless autumn night.

Hue is no less deceptive than brightness. White, black and the intermediate greys are distinguished from the rainbow colours, but in fact this distinction is to a large extent relative and subjective also. This can be seen by a very simple experiment. Take a disk of white cardboard and cover one half with black velvet or good-quality matt black paint. On the other half glue or paint concentric black strips as shown in Fig. 5 (Benham's top). Then fix the disk on a stick like a

FIG. 5. Benham's top.

wheel and spin it as one would spin a top. If this disk is illuminated by a bright white light, e.g. sunshine, at a certain speed coloured circles will appear on the disk and not the expected grey colour. Though these colours are dark and unsaturated, they do show that under certain conditions coloured forms can be produced by blending black and white.

We thus come to the disconcerting conclusion that visual perceptions can never be relied on for a definition of light. It is precisely for this reason that only the geometric properties of light rays were clear to men of science for over two thousand years. The rest which was deduced from subjective visual impressions remained mysterious, obscure and indefinite for ages.

* On closer examination there is also a third quality which may be called *saturation*. For example, in comparing two equally bright red surfaces side by side, we can say that the colour of one is purer and that the other is lighter in tint as if diluted with white. The added "whiteness" serves as a measure of the lack of saturation.

Sir Isaac Newton (1642–1727) (from life drawing by Steclay).

The science of optics was brought out of this deadlock only in the seventeenth century. Sir Isaac Newton was finally able to translate the subjective sensations of brightness and colour into the objective language of measurements, numbers and physical laws. In 1665 he began experiments on sunlight. In these experiments a beam of sunlight penetrated a circular hole in the shutter of his window striking a glass prism. The beam was refracted in the prism and an elongated image was cast on a screen with the rainbow sequence of

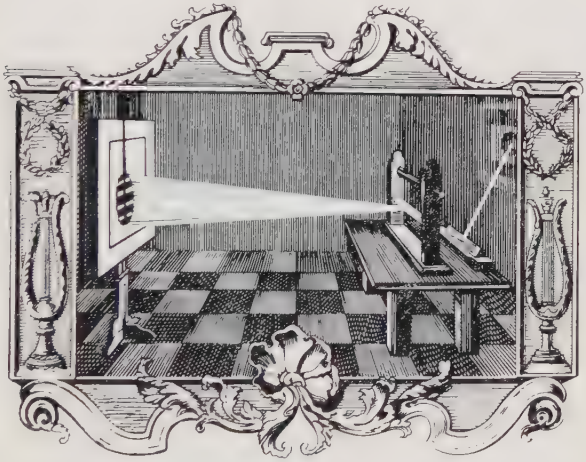


FIG. 6. Apparatus for the prismatic resolution of sunlight in a dark room of the Chamber of Arts, Petersburg Academy of Science, in the first half of the eighteenth century (from drawing by Academician Kraft).

colours. It was known long before Newton that the transmission of light through a prism would produce such a rainbow (spectrum), but it had been attributed to the effect of the glass in altering the colouring. Newton came to the conclusion that this was not so, and that white light is a complicated mechanical mixture of an infinite variety of rays which are refracted to different degrees in the glass. A prism does not change white light, it simply resolves it in its elemental constituent parts which can be blended back into their original white (Fig. 6). If a pure ray, for instance red, is separated from the rainbow fan of the prism and passed through a second prism, no further re-arrangement takes place. Something constant must therefore have been separated

in the first prism. However, the chromaticity of a simple constant colour does not in itself reveal anything new about the nature of light and as before it still remains relative and subjective. By mixing simple red and green, for instance, yellow is produced like one of the pure rays of the solar spectrum; by blending green and violet, we get blue and so on. In this respect the eye is unable to distinguish complex colours from simple colours and a prism or a spectral instrument is required which will arrange the light *spatially* in its simple colours.

It is precisely this *spatial separation* of the simple colours, and not their difference in colour, which placed in Newton's hands the first objective and quantitative characteristic of light corresponding to its subjective chromaticity. As shown by Newton, the spatial separation of the simple colours is due to their different refraction in the prism. Refraction can be associated with a definite number, an index of refraction. Thus Newton finally succeeded in taking the science of light out of the indeterminacy and muddle of subjective impressions onto the straight and stable road of mathematics.

After Newton, further study of the refraction of light in different bodies revealed that refraction greatly depends on the material from which the prism is made. In ordinary glass and quartz prisms the blue rays are refracted more than the red as in a rainbow, but if very thin prisms are made from dyes such as fuchsine, spectra of quite an unusual kind are obtained in which the red rays are refracted more than the blue. Thus, the index of refraction was a complex characteristic which depended on the quality of the light as well as on the kind of prism.

But Newton had also discovered another surprising property of pure rays which permitted their quantitative definition independently of the nature of the substance. If a slightly convex eye-glass is placed on a glass plate and illuminated with white light, a number of concentric iridescent rainbow rings appear around the point where the lens and glass make contact. Instead of illuminating the glass with white light, Newton carried out tests with the pure rays produced by the breakdown of sunlight by a prism. A still more surprising pattern was then disclosed. When, for instance, red rays were tested, numerous regular concentric alternately red and black rings appeared around the point of contact (Fig. 7). The rings came closer together with increasing distance from the central dark spot. By measuring

the radii of the dark rings, Newton found that they were a distance apart proportional to the square roots of consecutive even whole numbers, i.e. $\sqrt{2}, \sqrt{4}, \sqrt{6}, \sqrt{8}$.

When the lower glass plate was taken away and the lens was placed on a surface which did not reflect light, the rings disappeared. Newton discovered that it was necessary for there to be a thin layer of air (Fig. 8) between the lens and the glass for the rings to appear. It was easily proved geometrically that the thickness of the gap corresponding to each successive light and dark ring increases as the consecutive whole numbers. The thicknesses of the layers opposite each

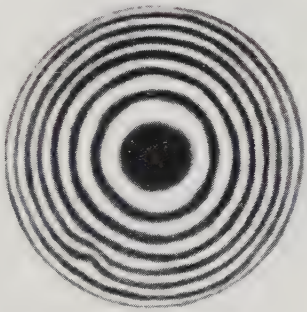


FIG. 7. Newton's rings.

ring are multiples of that opposite the first and smallest. The width of the rings changes if the lens and glass are illuminated with different simple colours; for red rays, the rings are widest, and for violet rays they are narrowest. Each particular simple colour has its own corresponding width for the first gap. Whatever lens is used, provided it is made of suitable material, this width remains constant for a given colour. It only changes if the gap is filled with some other fluid instead of air. In this case the width of the rings will depend on the index of refraction of the fluid.

These simple experiments, which can easily be repeated (they are even simpler than those with the prism), led to quite startling results. In the first place, they revealed the existence of a kind of regular *periodicity* in the flow of light. No less remarkable is the fact that the reflected light looks dark even if the entire surface of the lens is

uniformly illuminated by the incident rays. However, the question of periodicity is best considered at a later stage.

Just now it is important to establish that each pure colour can be related by Newton's rings to a definite thickness of the gap between the lens and the glass corresponding to the first dark ring. A pure colour can be defined quantitatively by the width of this first gap instead of by the index of refraction (Fig. 8). This is conventionally referred to as the wavelength and it is represented by the Greek letter λ. The wavelengths of visible light, as shown by Newton, are extremely small and they are usually measured in special units called millimicrons (a millimicron $m\mu$ is equal to one millionth part of a millimetre). Newton found, for instance, that the wavelength corresponding to the colour at the boundary of the green and blue parts of the solar spectrum was $\lambda = 492\ m\mu$. The wavelength of the red limit is about 700 $m\mu$ and the violet 400 $m\mu$.

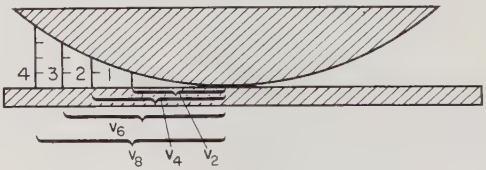


FIG. 8. Origin of Newton's rings.

The profound significance of Newton's experiments is worth pondering over. For thousands of years scientists had been unable to systematize the subjective aspects of light phenomena and now, suddenly, these phenomena could be approached objectively and subjected to precise scientific analysis.

In 1675, while Newton was still engaged with prismatic colours and rings, the astronomer Römer determined the *speed of light* from astronomical observations and estimated it (with modern corrections) at 186,000 miles per second. It takes about 8 minutes for light to travel from the sun to the earth. The ancients, who believed ocular beams were emitted from the eye to the sun, had concluded that the speed of light must be extremely high. The most distant star could be seen as soon as one opened one's eyes. A speed of 186,000 miles per second was a snail's pace compared with the speed at which ocular beams were supposed to travel. If that were the speed of ocular beams, we should not see the sun for 8 minutes after opening our eyes.

After Römer the speed of light was measured many times by different methods on earth and in the atmosphere by astronomers. The speed of light is now known with very great accuracy. For space devoid of matter, it is 299,776 km/sec. Here the first five figures are known with complete certainty, and it is only the last, the sixth, about which there is now any doubt. It is important to realize that the speed of light is independent of the wavelength in free space; it is the same for both red and blue rays. This is proved with great accuracy by the fact that there is no notable change in the colour of a star during an eclipse, as happens when one of a pair of binary stars puts the other in shade. Even if the speed of the various simple colours were only slightly different, the colour of a star would change considerably during such an eclipse.

The speed of light does, however, depend on the wavelength when propagated in matter, i.e. in water or in glass; this is the reason for the extension of light into a spectrum by a prism. By observing the rainbow in the sky it can be seen with one's own eyes that the rate of propagation of rays of different colour in droplets of water is different. This speed can be determined by dividing the speed of light in free space by the index of refraction. The index of refraction is itself equal to the ratio of the speed of light in free space to the speed of light of that particular colour in matter.

If the speed of light is divided by the wavelength, we then know the number of changes taking place in a ray of light per second, i.e. we know what is called the *frequency of light.*

Suppose we put ν for the frequency, c for the speed of light, and λ for the wavelength. Then

$$\nu = \frac{c}{\lambda}.$$

The frequency of visible light is enormous, for example, for yellow light with a wavelength of 600 mμ, it is equal to half a million billion cycles per second.

There is, however, one very important feature of the frequency of light. As we have seen, the speed of light is inversely proportional to the index of refraction of the medium. Likewise, from Newton's experiment, the wavelength λ also depends on the medium in which the light is propagated; Newton's rings contract if the gap between the lens and glass is filled with water instead of air. The wavelength, like

the speed of light, is inversely proportional to the index of refraction of the medium. Consequently, the quotient of the division of the speed of light by its wavelength, i.e. the frequency ν, is independent of the medium. This is a very important quantitative characteristic of light itself, i.e. its chromaticity.

But light is not completely defined by its speed and frequency. We know from subjective impressions that the brightness of light can vary within very wide limits. To appreciate the enormous difference in degrees of brightness, it is sufficient to compare the shimmer of a glow worm with the direct light of the sun.

But, physically speaking, what is the *brightness* of light? Science was only able to provide a real answer to this question after the concept of energy had been studied. There is no doubt that light always conveys energy which is evident from the effects of heating and chemical change which it produces; in general, we can only recognize the presence of light by its action, i.e. by the consequences of the energy which it bears. The perception of brightness is closely associated with the energy of light rays. The brightness of a simple "monochromatic" (single-colour) beam is greater, the greater the energy which it transfers.

The human eye is a very poor judge of the energy of light. At night a shining glow worm can seem dazzling, but yet the eye can withstand direct sunlight during the day. In comparing different colour beams, a red beam with great energy will seem less brilliant than a green beam with much less energy. Energy and brightness are therefore mutually related, though profoundly different. Owing to this indefiniteness, physicists now employ objective methods of measurement.

At this point a recapitulation will be of value. Having discarded the arbitrariness and diversity of subjective visual perception, we can now state that light is a carrier of energy which is propagated in outer space at a speed of about 186,000 mi/sec and possesses periodic properties. It is assumed that everything which comes within this definition is light whether or not it causes visual impressions. Later we shall see that this definition needs to be enlarged and qualified, but it is useful to adopt it for the time being.

In fact, since the early nineteenth century, physicists have discovered new kinds of invisible rays which make the visible spectrum seem infinitesimal by comparison. Newton's solar spectrum has been

extended at both limits, the red and the blue, into the darkness. What is concealed in this shade? The eye sees practically nothing at all.

In 1800 Herschel performed a very simple experiment. He placed a thermometer with a black bulb in the dark region at the red end of the solar spectrum and found that the temperature became perceptibly higher, i.e. in this region there are rays which cause heating but which are invisible to the human eye. These rays were called *infra-red*; he succeeded in measuring their wavelength and proving that they were propagated with the usual speed of light and that they therefore corresponded in all respects to the physical definition of light. The range of infra-red rays extends very far. Rays have now been detected with a wavelength of approximately 0·3 mm. They extend from the visible red boundary at 750 mμ to 300,000 mμ at least. But even this is not the limit of the spectrum. The electromagnetic waves which are broadcast by radio stations are also propagated at the speed of light and possess periodicity; they too must be regarded as light waves. Such waves can be produced in a wide range of wavelengths from scores of kilometres to fractions of a millimetre.

The red boundary of the spectrum can be traced as far as the practically extremely long waves used in wireless. Consider now what lies at the other end of the spectrum beyond the violet boundary. Here a thermometer is not notably heated, at least by usual sources of light, but if a photographic plate is placed there, it will darken when developed. *Ultra-violet rays* which are invisible can be detected by this and other methods. Under the action of these rays many bodies begin to glow with visible light (luminescence), become electrically conducting, or emit electrons (photo-electricity). Ultra-violet rays are usually considered to extend from the visible violet boundary (approximately 400 mμ) far into the region of shortwaves to at least 10 mμ. This is not the end of the spectrum. At the end of the last century Roentgen discovered X-rays, which, as we now know, possess all the properties of light rays. They, like the ultra-violet rays, act on photographic plates, cause visible luminescence and produce electrical effects. X-rays (depending on the method of producing them) range from about 10 to 0·1 mμ. But this is still not the end of the light spectrum. Beyond the X-rays there are rays with still shorter wavelengths which are known as gamma-rays which are radiated by radium and other radioactive substances. There are no grounds to

draw any limit to the gamma-rays, and wavelengths shorter than 0·001 mμ are known.

It may be said that in nature there are light rays of all kinds, beginning from the extremely long wavelengths to the extremely short. The small band of visible rays (from 400 to 700 mμ) is lost in this diversity.

Light has other remarkable properties. Consider Fig. 9*a*. The glass vessel contains a turbid mixture of water produced by drops of milk

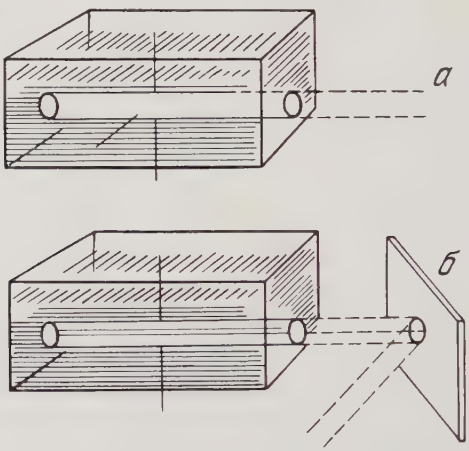


Fig. 9. Polarization of light upon reflection.

and a beam of sunlight is transmitted through it. The path of the light beam is clearly visible owing to the dispersion of light by the particles. At first sight it would seem that the light must be scattered in the same way on all sides whether the light path is seen from the top or the side. For a direct ray of sunlight, that is what actually happens.

But now consider Fig. 9*b*. Suppose that the ray strikes a mirror at an angle of about 54° (the ray is perpendicular to the plane of the drawing) and is then reflected through the mixture. By looking at the path of the light beam on all sides, an astonishing phenomenon is observed. From the side the scatter is very great (a comparatively bright band of light), but from the top there is practically no scatter and the path cannot be seen. The reflected light from the mirror has acquired a new and strange property: it only acts sideways and not up and down. Preferential directions of action appear in the

cross-section of the beam; it acquires *polarity*. Just as a bar magnet is most active along a line between its poles, and almost entirely inactive in the transverse direction, so with light, its action is in this case concentrated in the horizontal plane. This property of light (shown in the more complicated case of "double refraction" of Icelandic spar) was called *polarization* by Newton in analogy with the magnet. An ordinary beam of light is a mixture of rays which are polarized in all directions; polarization is therefore not detected. On reflection from a mirror the reflected rays have a definite polarization and the phenomenon therefore becomes noticeable. The property of polarization is possessed not only by visible light rays, but in general by all those which we call light rays, from radio waves to gamma-rays.

The majority of people cannot tell polarized from non-polarized light. Approximately 25 to 30 per cent of the population possesses this faculty, although they hardly ever suspect it. When looking at a surface which is radiating polarized light, such persons see a pale lemon-yellow coloured band, shaped like a slightly bent sheaf of wheat, in the centre of the field of vision. If the plane of polarization is rotated, this band is seen to turn with it. When the sun is in certain positions in the sky, the light coming from the sky is greatly polarized owing to the scattering of the sun's rays in the atmosphere and persons who possess this particular faculty see the faint yellow sheaf-like band in the sky.

A vivid description is to be found in a few lines of the book *Youth* by Tolstoy. In 1855, without apparently suspecting the physical significance of the phenomenon, he described this yellow polarized band in the sky while it was still hardly known amongst scientists (it was first described by Haidinger in 1846)*. The following lines from Chapter XIII are a rare example of a great artist's subtle power of observation:

". . . I would find myself laying my book down, and gazing through the open doorway on to the balcony at the pendant sinuous branches of the tall birch trees where they stood overshadowed by the coming night, and at the clear sky where, if one looked at it intently enough, misty *yellowish* spots would appear suddenly, and then disappear again".

The reader is recommended to test his eyes and try to see the yellow

* See the note by B. I. Pilipchuk "Concerning the youthful observations of L. N. Tolstoy", No. 2, 92, (1945).

polarization band in the sky. Some readers will find that their eyes possess a faculty which they did not know about. It is best to observe light which is reflected from glass which has its rear side painted black. At a certain angle of incidence and reflection such a plate will polarize light quite considerably.

During recent years methods of mass producing transparent films of any size have been found which polarize light completely. One such "Polar" is made from plastic (vinyl alcohol). A thin film of vinyl alcohol, stretched in one direction, is subjected to the attack of iodine vapours and after this it is capable of polarizing light completely. Polars are now widely used in laboratories, in engineering and photography. If any illuminated surface such as the sky or a wall is looked at through a polar, the yellow sheaf-like band is always visible provided the eye of the observer possesses the faculty. If the polar is turned, the band turns with it.

The physics of light polarization will be considered presently. Meanwhile, consider another remarkable property of light.

In a uniform medium light travels in straight lines and a small obstacle in the path of the light will hide the source. The ancients produced their orderly science of geometrical optics on this basis. It is not, however, always true. Look at a bright light about 20 to 40 yards away through two fingers and press them tightly together so that only a very narrow slit is left. Instead of a bright point we see a band across the slit with a bright spot in the centre and an array of alternate dark and rainbow-coloured strips which is at variance with the supposed rectilinearity of light propagation. This phenomenon was naturally known to men in ancient times. The rectilinearity of light is also disturbed, for instance, by the presence of the eyelashes when squinting and this is known only too well by children. The importance of this phenomenon was, however, not pointed out until the seventeenth century by Grimaldi.

Figure 10 shows the results of experiments carried out by Arkad'ev in which the shadow cast by a hand holding a dinner plate was photographed. The first photograph (on the left) was taken with a distance a of about 2 yards between the light and the hand and a distance b of about 1 yard between hand and screen. In the second photograph $a + b$ was about 1 mile, in the third 4 miles, in the fourth 18 miles, and in the fifth 145 miles. Whereas the shadow is quite distinct in the first photograph, in the later photographs it becomes

more and more blurred. The distant light point is reproduced in the centre of the shadow cast by the plate and the shadow of the hand is lined with dark and light bands. Hence light cannot be assumed to travel in straight lines. According to geometric laws, rays from a small light at such a distance should produce an impeccable shadow.

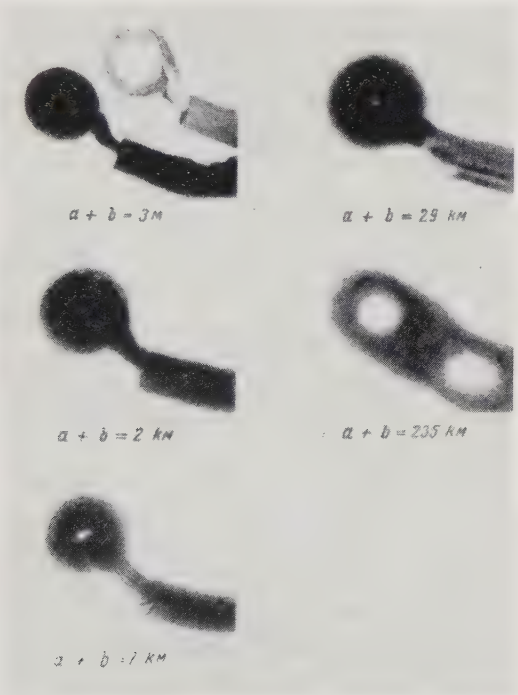


FIG. 10. Diffraction of light when passing an opaque object (experiment by V. K. Arkad'ev).

Light bends around narrow slits and small objects in its path. Grimaldi called this phenomenon diffraction. Newton investigated the phenomenon and established that diffraction is independent of the type of material of which the slit is made or which forms the obstacle and he concluded that it was therefore a fundamental property of light.

Later it was proved that diffraction is a common property of all rays throughout the spectrum, from radio waves to X-rays. The shorter

the wavelength, the narrower must be the slits and objects to make the deviations noticeable.

Several of the most important specific properties of light have now been considered, namely, periodicity, velocity, polarization and diffraction. Taken together they indicate that light can be thought of as wave motion with transverse vibration. However, we must refrain from such generalizations until all the fundamental properties have been considered.

Light proceeds from matter, is generated in matter and, being absorbed, disappears in matter. If light and matter come together, an interaction always follows. On the one hand, matter reflects, refracts and absorbs light and can rotate the plane of polarization. The effect of matter on light even begins in outer space, for the rays of stars distant millions of miles away are deflected as if attracted to the sun; as a result the stars seem to be displaced in the firmament. On the other hand, light produces a variety of effects on matter. Light exerts pressure on matter, though slightly. Light produces chemical changes, viz. photographic films, vegetation, sun-tan, etc. Constituent parts of atoms (electrons) can be ejected from matter under the action of light (light dispersion, fluorescence, phosphorescence). On being absorbed, light causes a rise in temperature.

At the beginning of this century Planck made a most significant discovery. He discovered that light can only be absorbed and radiated in definite quantities of energy which he called quanta.

Consider the chemical effect of light. Take, for instance, a thin coloured piece of paper or cloth. In sunlight it gradually fades. The dye is made of minute particles (molecules) which are evenly distributed over the material. The molecules are identical and the same light seems to fall everywhere, yet the cloth fades gradually, i.e. first one molecule disintegrates and then another. With evenly distributed light and identical molecules, one might expect that all the molecules would disintegrate together, that none of them would disintegrate, or that the disintegration would occur suddenly after the molecules had absorbed sufficient energy. Yet the process takes place slowly and gradually. Why is this? Either the molecules are not identical, or else the front of the incident light cannot be homogeneous, i.e. the energy must be concentrated at some points and absent from others. There is no reason to doubt that all the molecules are identical. This is indicated by the whole of chemical practice. Hence the front of

an apparently homogeneous beam of light cannot in fact be uniform. Its energy is concentrated at spatially separated centres.

From tests on the other effects of light, and not only chemical effects, physicists have come to the same conclusion that the effects of light are produced as if matter can only absorb and radiate light in whole quanta. A light quantum is now called a *photon*.

For light at a frequency of ν cycles per second, the magnitude of a quantum is $h\nu$, where h is a very small constant ($6{\cdot}62 \times 10^{-27}$, i.e. 6·62 divided by a one followed by 27 zeros). The gradual fading now becomes comprehensible. The energy of the incident light is not evenly distributed over the material, but is concentrated at certain points. Only those molecules of the material disintegrate which have encountered the flying quanta of light. In some cases the following line of reasoning holds. If a substance absorbs energy E during a certain period of time, then the number N of disintegrated molecules is equal to the energy E divided by the energy of a quantum

$$N = E/h\nu.$$

This conclusion has been confirmed experimentally in certain simple cases of chemical decomposition under the action of light. All the effects of light follow the same quantum pattern, in heating, in the electrical effects of light, fluorescence and so on. Indeed, the human eye can detect the discontinuity of light energy in very faint light. This is considered in the last chapter.

For radio waves the frequency ν is relatively small and therefore the quantum $h\nu$ is negligible. In this case it is extremely difficult to detect the quantum pattern. On the other hand, for X-rays having a very high frequency, the quantum is relatively large and the quantum pattern is sharp and distinct.

Our list of the properties of light now includes a new property which appears to be inconsistent. Our list is still not complete, but in order to help the reader grasp the phenomena, it is useful at this juncture to consider previous attempts to explain them.

Many guesses have been made as to the nature of light in ages past. Many were groundless since the facts were not to hand. The properties of light lay concealed and vision was confused with light. Strange theories arose such as the ocular beams theory, considered in the Introduction. However, some guesses came fairly close to the truth.

Light carries energy from the sun to the earth over enormous distances. Even the ancients knew, or sensed, this.

How can energy be transmitted over great distances? There are not many ways in which this can be done. The simplest is to transfer energy together with matter. For example, a gun transfers the destructive energy of powder to a target by the projectile. Energy can also be transferred with matter in a continuous flow, by an avalanche, but this is essentially the same thing. In either case substance travels together with energy. But there is another method. The sea wave, lifted by the wind, is carried along and finally breaks on the shore giving away its energy. But if waves are examined closely, it is easy to see that while the wave goes on, the water does not go with it, but only heaves up and down in the same place. Energy is transferred from layer to layer without a transfer of matter. It is exactly in this way that the energy of sound is propagated in air. A sound wave is not wind, but the sequential oscillation of layers of air. "If air sped from a harp string as swiftly as the tune, i.e. at over 1000 feet per second, then such music would move mountains" (Lomonosov, *Treatise on the Origin of Light*). An intermediate medium is required for energy to be transferred by waves, in our examples water and air; sound cannot be propagated in a vacuum. No other methods of transferring energy are known. This implies that sunlight which transfers the energy of the sun to earth, must either be a stream of particles, or a system of waves in a medium, or both at the same time. These opinions existed in different forms even amongst the ancients and they were bound to be revived when the early physicists tried to relate all the various properties of light into a single whole.

Newton attempted to avoid confusing conjecture with fact and assumptions with reality, but in his works he returned many times to the question of the nature of light, where he favoured the corpuscular theory. His main objection to the wave theory was the absence of a medium in outer space for their propagation. The planets move with absolute regularity without encountering any resistance or friction in the space surrounding them; consequently, there are no grounds to suppose that a medium is present. Just like sound, which ceases to exist in a vessel from which all air has been evacuated, so with the mechanical oscillations of heavenly bodies which cannot be converted into waves in free space. According to Newton, it was more probable that light was a stream of minute particles of matter (corpuscles).

For him, the periodicity of light could be explained by the corpuscles rotating. The distance travelled by one corpuscle in one revolution would then be the wavelength. Newton regarded polarization as an attribute solely of solid particles, and he saw its presence as proof of the fact that light consists of solid corpuscles. The diffraction of light was attributed to the repulsion and attraction of matter.

But the legacy of knowledge which he left behind contained a serious objection to his theory of light. Consider once more the experiment with rings (Fig. 7). Doubtless these rings are due to the interaction (interference) of two rays reflected from the upper and lower boundaries of the gap between the lens and glass.

In Fig. 11, ray 1 is reflected from the upper boundary and produces the reflected ray 1; ray 2, being refracted at the upper surface, is

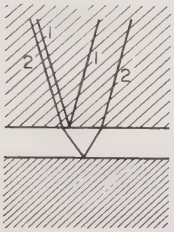


FIG. 11. Paths of rays in Newton's experiments with interference rings.

then reflected from the lower and re-enters the lens. These "interfering" rays meet and produce the constant pattern of Newton's rings. Now suppose, with Newton, that rays 1 and 2 are the paths of the light particles in disorderly flight from the light source. The particles are quite independent of each other. If very feeble illumination is employed, a state must finally be reached in which the probability of the particles passing along paths 1 and 2 at the same time becomes negligible. If Newton is right, the rings should disappear in such a case. The particles have nothing with which to interact or interfere. Tests have, however, shown that the same result is obtained no matter how low the intensity of illumination. For example, it is possible to make the illumination so feeble that several days are required to photograph the rings, but they finally show up just as distinctly.

Not for another 150 years was it shown that the ring experiments and interference could be explained by assuming that light is wave

motion. In fact, waves are propagated from a light source in all directions and no matter how faint some energy is conveyed; rays 1 and 2 can always interfere. Moreover, the wave theory predicted the result of interference quite accurately. If the difference in the path of the two rays 1 and 2 on meeting is such that the trough of one wave occurs at the crest of the other, then the waves as it were cancel out and the dark ring is produced; conversely, in the adjacent section where the crests coincide, they enhance each other and a bright ring results.

The new wave theory explained with equal success all the refinements of diffraction and it predicted facts which tests never failed to corroborate. The polarization of light was also clearly explained. The phenomenon of polarization shows that the light waves are

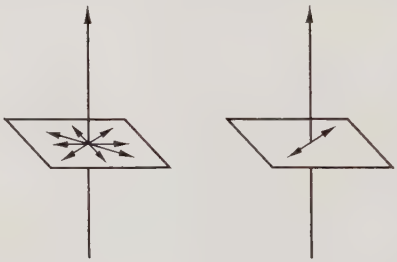


Fig. 12. Oscillation in non-polarized and in polarized light.

transverse, i.e. the oscillation is perpendicular to the direction of the ray as for waves on the surface of a pond. Non-polarized rays oscillate in all directions around the ray (Fig. 12).

The wave theory triumphed over Newton's corpuscular theory in the first half of the nineteenth century owing to the irreproachable qualitative and quantitative accuracy of its predictions. But how justified was this victory? It will be remembered that Newton's main objection to the wave theory was the absence of a medium (ether) in outer space. Had Young and Fresnel overcome this objection? No, they had not; they believed that the wave properties of light proved that there must be an ether. Throughout the nineteenth century physicists tried in vain to find direct proof, after experiments with the propagation of light through moving bodies. If an immobile medium did exist in which the light waves can be propagated, then for instance, the annual motion of the earth round the sun should be accompanied

by a kind of "ether wind" which would influence optical phenomena. No such "wind" was found. Consequently, either there was no ether, or else it possessed other properties which were at variance with the wave theory.

In spite of this, the wave theory obtained unexpected support from research into electrical and magnetic phenomena. It was shown experimentally that electrical and magnetic disturbances are propagated with the velocity of light; it was also discovered that electromagnetic waves are propagated in free space under certain conditions. Predicted theoretically by Maxwell, they were detected experimentally by Herz. Popov found a method of using electromagnetic waves for long-distance communication and thus laid the foundations of radio. Lebedev and others showed that electromagnetic waves possessed all the properties of light known at that time in that they were reflected, refracted, polarized and were capable of diffraction. In this way another property of light was discovered, its electromagnetism. This explained the interaction of light and matter. Matter, as we now know, is made up of electrically charged particles, positive nuclei with negative electrons around them. Any movement of these particles must generate electromagnetic waves, i.e. produce light. Conversely, when electromagnetic waves hit atoms and molecules, they put the charged particles in motion and the wave energy is scattered and absorbed.

Now let us return to the difficulty about the ether. The existence of the ether was essential to the wave theory of light. Without a medium, without the ether, waves could not exist any more than sound can exist in a vacuum. But as soon as it was proved that light rays are electromagnetic, the position was again reversed. Regardless of whether or not there was an ether, it was known by tests that an electrical field exists around charged bodies and if the charged body moves, then, according to the laws of electromagnetism, electromagnetic waves must appear. They exist by virtue of the electrical field.

It may of course be asked whether an electrical field can exist without a medium. It can only be answered that every attempt since Maxwell to deduce the laws of electricity and magnetism from the conception of a mechanical ether has been in vain.

Nevertheless, the electromagnetic wave theory of light seemed to have been proved conclusively at the end of the nineteenth century

and Newton's objection regarding the absence of a medium became unimportant as soon as it was clear that the light waves were non-mechanical.

The wave theory seemed to have won a complete and final victory. In optics all was "reduced to order". The victory was, however, very short-lived. In less than 5 years after the invention of radio, the quantum pattern of light behaviour was discovered which was inconsistent with the wave theory. How can energy be absorbed in discontinuous quantities if it is carried by continuous waves? More than 30 years have now passed and the same perplexity remains; the wave theory cannot answer this question today.

The wave theory was helpless before the quantum laws. The tables were turned so completely that one cannot resist the temptation to quote the words which Lomonosov used in deriding the corpuscular theory "Inconvenience is often the next-door neighbour of impossibility".

It was precisely this formerly "impossible" corpuscular theory which now had the best chance of recognition. No difficulties arise about the ether because the light corpuscles fly in free space and require no ether. The quantum laws also conform with Newton's theory. The molecules absorb light in whole quanta because either a whole corpuscle is received or nothing; therefore in light-induced chemical changes the molecules are not all decomposed at the same time, but only those which receive the corpuscle.

In reducing the brightness of waves, only their peak-to-peak amplitude, their intensity, is reduced, but in reducing the stream of corpuscles the effect of each corpuscle is the same as before and they are only reduced in number. The quantum laws, as far as the corpuscular theory is concerned, only require the light to be propagated in whole quanta (corpuscles).

But the revived corpuscular theory still could not explain interference, diffraction and other properties of light which were automatically solved by the wave theory.

The situation was intolerable and physicists had good cause to repeat the mournful commentary of Lomonosov in connexion with the theory of light, quoted at the beginning to this chapter. The two quite different theories of the nature of light each reigned in its own province and remained powerless in the other.

The solution was inspired from a very unexpected source. It will be

recalled that light has two main features, colour and brightness. We have dwelt at length on the everyday observations which show that a mechanical transfer of energy is only possible by particles or by waves. Some form of combination was of course conceivable, but no other possibility, even if it had been expressed, would have been understood.

Classical mechanics, which like optics, was founded by Newton, is a mathematical generalization of our everyday experience and its conclusions in no way differ from our simple deductions as far as methods of transferring energy are concerned. Classical physics rests on the proposition that Newton's laws are the complete unassailable truth. This conviction gave rise to a "mechanistic" form of natural science which endeavoured to explain all natural phenomena through the movements of particles bound together by certain forces which are governed by Newtonian laws.

The basis for the belief in the infallibility of these laws was, in the first place, their *comprehensibility*, their complete correspondence with our own ordinary non-scientific ideas, and secondly the enormous *success* of classical mechanics in all branches of natural science and engineering. These justifications of Newton's laws are, however, far from faultless. We say that something is "comprehensible" if we are accustomed to it. For example, we compare a flying atom with a flying bullet and picture the atom by the more customary image of a bullet. But it is clear to everyone that a bullet is immeasurably more complex than an atom and our "explanation" reduces the simpler to the more complex, but familiar. The "comprehensibility" of certain laws or phenomena is no guarantee either of their simplicity or their authenticity. On the other hand, mankind is historically developing, his customs change, and what has been incomprehensible is gradually comprehended. Our accustomed ideas largely correspond to a certain stage of development and as mankind develops men come closer to comprehending the truth, whilst to speak of complete coincidence between our ideas and absolute truth implies the denial of the incontrovertible truth of evolution. In short, the belief in a "mechanistic" nature and the infallibility of Newton's laws rests essentially on the very shaky foundation of custom.

At the turn of the century seemingly insurmountable contradictions were discovered in the properties of matter and light. The mass of a body was dependent on its velocity and even the concepts of space and time needed to be revised. Some physicists and philosophers

spoke of the "de-materialization" of matter and said that "matter has disappeared, only equations remain". Mechanistic and metaphysical materialism was in such a state of deadlock that some scientists changed their minds and openly or disguisedly took to the haze of idealism and mysticism.

The "insurmountable" contradiction between the wave and corpuscular theories of light at this stage in the development of optics is an expression of the dialectics of nature, of the real unity of contradictions. The simplified mechanistic ideas of classical physics concerning continuous waves and discontinuous particles, which seem to be mutually exclusive, co-exist in nature. We may be unaccustomed to such conflicting unity, but this only indicates the inadequacy and primitiveness of our mechanistic ideas.

The real world is infinitely more complex than the simplified metaphysical images to which we are accustomed in our habits and everyday experience.

The course of science has confirmed the truth of this. The achievements of classical mechanics together with the high perfection of experimental technique ended in impotence and helplessness before new facts.

The existing material world (matter in motion) is represented in two main forms, as *matter* and *light*. Gradually it has been established that matter in all its forms consists of negatively charged electrons, positively charged protons and neutrons which have no charge. Matter is therefore more comprehensible than light which behaves like waves and particles simultaneously. Although it seems absurd to think of "stationary light", mechanical physics was quite reconciled to "substance at rest". A wave is inconceivable without motion. If a physicist speaks of "standing waves", he has in mind the addition of the two similar waves travelling in opposite directions. On the other hand, a particle taken separately can be represented as perfectly stationary. But such a form of material, deprived of motion, i.e. deprived of its inalienable property, is a pure abstraction from the point of view of dialectical materialism. It was this approach which provided the new and unexpected answers. In experiments first carried out about a quarter of a century ago, it was discovered that streams of electrons, protons and molecules, meeting small obstacles and slits, display the same distinctive diffraction pattern as light, i.e. they possess all the fundamental properties of waves.

Figure 13 shows a specimen diffraction pattern obtained in the transmission of electrons through a very thin layer of silver consisting of microscopic crystal particles. The diffraction here is no less distinct than in the case of light, which demonstrates the wave nature of electrons, i.e. of matter.

The wavelength of these "matter waves" can now be measured with great accuracy and is equal to h/mv. Here h is again a constant ($6{\cdot}62 \times 10^{-27}$), m is the particle mass and v is the velocity.

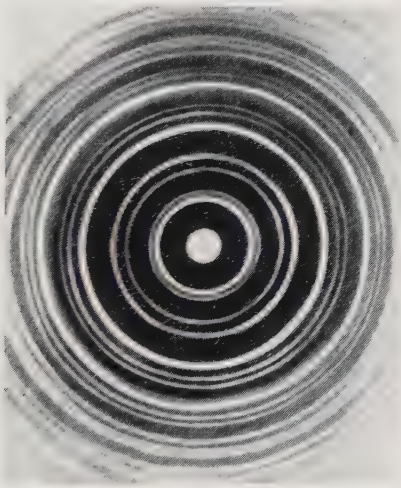


FIG. 13. Diffraction of electrons in transmission through a very thin layer of silver.

It is not only the elementary particles (electrons, atoms and molecules) which correspond to waves, since there are good grounds for stating that any individual accumulation of matter, whether it be a man, a bus or the sun, is characterized by a wave as befits its mass and velocity.

In the whole history of natural science it is difficult to point to another discovery which is so surprising and which breaks so sharply with our customary ideas.

The same has happened in mechanics as in optics. Ancient teaching assumed that a light beam was a shaft of rectilinearly propagated rays, but the phenomenon of diffraction made it evident that light is wave

motion which only behaves like a pencil of rays in the absence of small obstacles and apertures. Wave optics was latent in the geometric ray optics of ancient times. The mechanics of Newton was "ray mechanics", but the discoveries of the present time have shown that the more general "wave mechanics" was latent in it too.

Yet "matter waves" are not to be confused with light waves. We have seen that light waves are of an electromagnetic nature, which cannot be said of matter waves. Matter waves are an organic part of matter itself, its particles, whereas light waves are radiated by matter and have entirely different properties.

It is wrong to suppose that the corpuscular theory has again been replaced by a more refined theory of waves. We are just as sure that particles of matter, atoms and electrons, exist in matter and that quanta exist in luminous flux, as we are that matter and light waves exist. There have been attempts to treat matter as a mechanical combination of particles and waves, the waves playing the role of a pilot which steers the particle according to the laws of wave propagation. At first sight the opposite mechanical assumption is equally tenable in that the waves could be produced by particles in the ether in the same way as ships leave wash in their wake. Such speculations, however, are not based on fact.

Another widely held opinion is that in some experiments (e.g. in the experiment with Newton's rings) light behaves as in wave motion, but that in other experiments (e.g. in the discoloration of a dyed cloth) light behaves like a stream of particles. This, however, is erroneous too.

If Newton's rings experiment is carried out with extremely feeble light, under certain conditions it is possible to observe statistically irregular variations of brightness of the light rings which testify to the fact that even in this typical wave phenomenon the energy of the light is concentrated at individual centres (photons). On the other hand if a dyed cloth is illuminated through narrow slits, diffraction patterns are revealed in the process of discoloration.

Matter, i.e. substance and light, possesses the properties both of waves and of particles simultaneously, but as a whole matter is not waves or particles, nor a mixture of the two. Mechanistic conceptions are incapable of grasping reality in its entirety, owing to the lack of visible evidence.

A formal mathematical theory of light, though not yet perfect, covers almost the entire sphere of known phenomena. This theory

however remains extremely abstract and "incomprehensible" (in the sense of a lack of visible evidence).

We are now in the position to take up the question which we left at the beginning of this chapter. The reader has probably not forgotten that we met with difficulties in defining the object of our study. Has this now been cleared up? In principle, yes. Gradually the fundamental objective properties of light have been established which distinguish it from other types of matter. But the application of the distinguishing features, particularly in their totality, sometimes presents difficulties in practice to this day.

At the end of the last century physicists were for a long time undecided whether cathode rays were substance or light. The question was eventually settled by experiments which proved that cathode rays have a negative electrical charge. For a long time it was also in doubt whether X-rays were light. Only after the diffraction of X-rays was detected in 1913 did physicists finally agree that this was so. Strictly speaking, of course, this conclusion still awaits verification since diffraction also occurs in beams of charged particles, electrons and protons, and uncharged neutrons, as well. It was only the aggregate of all the various phenomena, pointing to the electromagnetic nature of X-rays, which proved that they were a form of light.

In the course of several decades investigators have radically altered their opinion about the nature of cosmic radiation from outer space which possesses enormous penetrative power. Twenty years ago it was regarded as established that the bulk of cosmic rays consists of light rays with a very short wavelength, shorter on average than the gamma rays emitted by radium. However, it has since been proved that cosmic rays are deflected by the magnetic field of the earth and therefore consist of electrically charged particles. At first it was supposed that primary cosmic radiation consists of electrons. But recent investigations, and particularly those of Soviet physicists, in the upper layers of the atmosphere, have proved without doubt that the bulk of primary cosmic radiation consists of positively charged protons. It should be noted that cosmic rays are propagated at enormous velocities practically equal to the speed of light.

These examples show how difficult it is to establish in particular cases whether or not a given phenomenon is of an optical nature.

The more scientists delve into study of matter and its different manifestations, substance and light, the more inexhaustible the subject

seems to be. Despite the many similar properties of substance and light (the properties of waves and particles and quantum laws), light and substance have until recently been regarded as essentially different in much the same way as the sound of a violin differs from the violin and the radio waves from the radio transmitter. But about 20 years ago another remarkable discovery was made.

Using his formal mathematical theory of light, Dirac arrived at the theoretical conclusion that under certain conditions light is transformed into substance and vice versa. In the strong electrical field of

FIG. 14. Formation of an electron-positron pair from a gamma light quantum. In the magnetic field (above) the positron is deflected left and the electron to the right (photograph by A. V. Groshev and I. M. Frank).

an atomic nucleus, light quanta with a wavelength of about 0·001 mμ, can transform into two oppositely charged particles, electrons and positrons. His astonishing prediction has been completely confirmed by tests. Figure 14 shows a photograph of this process. Such photographs can be taken because high-speed charged particles travelling through air saturated with water vapour leave traces formed by condensed droplets of water. The oppositely charged particles, the electron and positron, pass through a strong magnetic field so that they bend in opposite directions.

This photograph shows the amazing spectacle of a gamma ray

turning into two particles of substance. This is something fantastic like the transformation of a melody into a violin!

There is as yet nothing to explain this phenomenon of science except the formal and, therefore unsatisfying, mathematical theory of Dirac. There is no doubt, however, that a profound and as yet unsuspected relationship exists between light and substance. Man has mastered one more aspect of nature.

* * * * *

We began with the subjective visual sensations of colour and brightness and then, step by step, tracing the history of optics, we came to the present complex state of objective science. The reader is probably dissatisfied with the end of the story and the fate which has befallen so many theories of light. The mystery has not been unravelled and it now seems more involved than in the days of Newton and Lomonosov. But the same situation arises in all fields of knowledge today. The closer we come to the truth, the more we see its complexity and inexhaustibility. The continual battles for truth, victorious, though never finally triumphant, are, nevertheless, undeniably justified. In trying to understand the nature of light man has acquired the microscope, telescope, range-finder, radio, and X-rays. The same investigations have helped to harness atomic energy. In the pursuit of truth man boundlessly extends his mastery over nature. And is this not the real purpose of science? The history of light is still in the making; new discoveries undoubtedly await science in this field. We shall come closer to ultimate truth and industry will be enriched with new means and methods.

THE SUN

The sun abides in the centre of everything. Nor would anyone place this luminary in this beautiful temple in any other better position than that whence it can illuminate everything equally. Not without grounds, therefore, do some call it the Light of the World, others Reason, still others the Ruler, Trismehist the Visible Deity, Sophocles' Electra—the All-Seeing. As if seated on his royal throne, the sun rules his family of stars.

Copernicus

THERE is a saying by Kozma Prutkov:* "If you are asked which is the more useful the sun or the moon, make answer 'the moon' for the sun shines in the day-time when there is enough light without it, while the moon shines at night". Naturally, no one is misled by this witty nonsense because there would be no light except for the sun and there would be no moon at night if the sun were not shining elsewhere, since the moon only reflects its light to earth. In screening ourselves from the direct rays of the sun with the brim of a hat or a parasol, the sun still illuminates the air, the clouds, the fields and all that surrounds us. The sun may be concealed behind cloud, but its rays are scattered by the air and it illuminates the earth just the same. Only if a large opaque object comes between the earth and the sun at a large enough distance can the direct rays of the sun be shut off from the earth's atmosphere and darkness prevail. This is what happens during a solar eclipse when the earth, moon and sun lie in the same straight line. The position is illustrated in Fig. 15.

* Kozma Prutkov, a fictitious writer of nonsense verse and ponderously amusing sayings. He never existed, but four men including A. K. Tolstoy wrote up his "works".

N. Copernicus (1473–1543).

Light (in the sense of visible and invisible rays) may be said to emanate from three different sources. The earth receives the *direct* rays of the sun which we try to avoid seeing. Our eyes are usually directed horizontally to the earth and the sun is only in front of our eyes at sunrise and sunset. Scattered rays reach us from the sun continuously during the day. The blue of the sky is the result of scattering by molecules of air. If the scattering particles are very small, rays with short wavelengths are scattered most (in the visible spectrum these are the blue and violet). If the particles are large, the

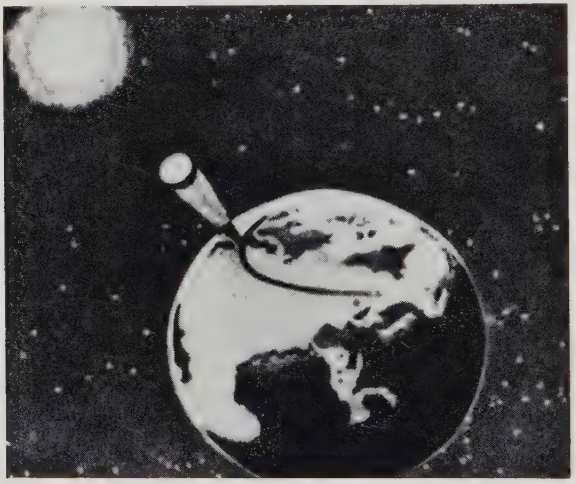


FIG. 15. Solar eclipse.

longer wavelengths are scattered as well. This can easily be seen when smoking a cigarette. The colour of the smoke from the lighted end is blue, but that from the mouthpiece is white. The explanation is that the particles of smoke passing through the tobacco coalesce and become large. In exactly the same way, the clouds which consist of large particles of moisture are white in colour, whilst the clear sky is blue. If the earth had no atmosphere, we should then see the sun against a black sky.

At an altitude of about 13 miles observers on stratospheric balloons have seen an almost black sky above them with the sun shining brightly.

Sunrise and sunset, the green of the fields and woods, the whiteness

of the snow, the gleaming of the moon, all is the reflected or scattered light of the sun.

But other rays reach us independently of the direct and scattered light of the sun. Any heated body radiates light. If the temperature is very high, many visible rays are present in the light; if the temperature is low, invisible infra-red rays are radiated, which can be detected by their thermal effect. Everything about us contains heat. If we say that one body is hot and another cold we are only speaking relatively in relation to body temperature. To make something completely cold, implies that all motion of its particles has been stopped. Such chilling is only possible at temperatures of approximately —273°C (absolute zero temperature). On earth everything is warm and therefore everything is alight with visible or invisible rays; man himself is alight and so are his eyes. In this sense the ancients were correct in attributing a "mild inner fire" to the eye. The energy of these internal rays of the eye is such that if the eye could in fact sense them, as for instance it does green rays, it would be accompanied day and night by luminosity equivalent to about five million candles (see the end of the next chapter).

We receive the visible rays of the stars, distant suns, and nebulae; sometimes flashes of lightning rend the heavens or the fantastic northern lights suffuse the sky. Fire-flies glow at night in the summer verdure and tree stumps phosphoresce in the forest. Lightning radiates invisible electromagnetic waves as well as visible light; even in clear weather interference crackling can be heard on the radio, the result of electromagnetic discharges in the atmosphere. Such discharges led Popov to the discovery of wireless. In recent years it has been proved beyond doubt that the sun and stars also emit radio waves. During the Second World War the radio radiation of the sun and other heavenly bodies sometimes interfered with radar protection. In the earth's crust the atoms of radioactive substances are slowly disintegrating and this is accompanied by the radiation of light, gamma rays with very short wavelengths.

Besides this light which is attributable to natural causes on earth and in the universe, man has also made artificial sources of light for his own convenience. He lights wood, paraffin, candles and uses electric bulbs in which metallic filaments are heated by electricity. In modern fluorescent lighting the electric current produces a discharge in mercury vapour which is accompanied by the emission of

ultra-violet rays. These rays are then absorbed on the walls of a glass tube coated on the inside with a luminescent compound and converted into visible light. Any radio broadcasting station is a kind of light source which transmits very long wavelengths. X-ray tubes, used for scientific and medical purposes, radiate an invisible light that passes through the human body without difficulty.

But the energy of all this light, whether separately or altogether, is infinitesimal compared with that of the sun. In the last analysis, by lighting a lamp, operating a radio station or using an X-ray tube, we are in fact consuming a minute part of the sun's energy accumulated by plants in the form of coal, oil and wood. In using the energy of the wind, waterfalls or reservoirs, we are again using the luminous solar

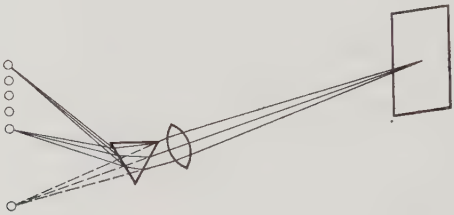


FIG. 16. Spectroscope (drawing by Newton).

energy which caused the wind and raised the water. It is therefore clear that no artificial source of light can rival the sun in radiated energy.

The reason why man has to use his own modest artificial sources of light during the day as well as at night, is that the *spectral composition of light* is just as important as the total amount of light energy, if not more so.

We know that this important concept was first introduced by Newton. Newton's apparatus for the prismatic resolution of sunlight was the prototype of all the various kinds of *spectroscopes* now used in science. Figure 16, which is taken from a drawing by Newton himself, illustrates the fundamental principle of a spectroscope. The light strikes a narrow slit situated almost at the focus of a lens on the other side. After the lens the beam strikes a prism, is refracted, and then enters a telescope adjusted to infinity. An image of the slit of the spectroscope can be seen through the eyepiece of the telescope in each of the simple hues composing the colour under investigation.

If the slit is too wide, the images are superimposed on each other, the spectrum becomes indistinct, and the colours run together.

If a paraffin or electric lamp is placed in front of the slit, a continuous sequence of colours from red to violet is seen. A photographic film can be used instead of the eye and an additional short ultra-violet region can then be detected at the violet end. But neither the eye nor a film is suitable for judging the distribution of energy in the spectrum; each has its own narrow limited band of sensitivity. The eye is particularly sensitive to the green part of the spectrum, whilst an ordinary film is more sensitive to blue and violet. To judge the amount of energy, it is best to use a thermal instrument which

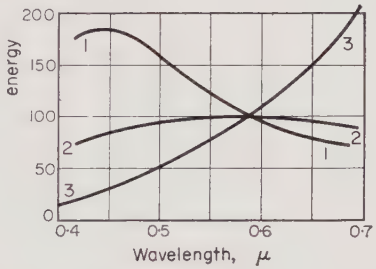


FIG. 17. Energy distribution in the spectra of various sources. Abscissa – wavelength; ordinate – relative energy.

absorbs the rays and converts them into heat. Unfortunately, such instruments, even if made with the greatest care, are far less sensitive than the eye or a film. Figure 17 shows the distribution of energy measured in this way for various types of light. The wavelength is marked off along the base in microns (it will be recalled that $0{\cdot}4\mu$ corresponds to the violet end of the visible spectrum, and $0{\cdot}7\mu$ to the red limit). Energy is marked off in relative units along the vertical axis, the energy at $0{\cdot}59\mu$ being assumed equal to 100 for each type of light. Curve 2 represents the distribution of energy in the visible part of the solar spectrum, and curve 1 represents that in the blue light of the sky; we see that the maximum of energy is shifted into the blue part owing to dispersion. Curve 3 illustrates the distribution of energy in the spectrum of an electric bulb.

If different solid bodies, say metals, are raised to an identical elevated temperature, their energy distributions will not be all the same. The difference is due to dissimilarities in the reflecting capability of

the surface of the heated body. Only if the surfaces are made perfectly black, i.e. if they completely absorb all rays and reflect nothing, will the energy distributions be identical at the same temperature.

In a heated body the energy of molecular motion is converted into radiated light and, conversely, the molecules absorb light. For each particular temperature there is an equilibrium position between absorption and radiation.

In the chapter on Light we saw that the radiation and absorption of light cannot take place other than in whole quanta $h\nu$. For the equilibrium between radiation and absorption of a body with a perfectly black surface, having regard to the quantum nature of both processes, we can deduce the energy distribution of the light radiated by a black body without difficulty. Historically the problem was solved the other way round for in searching for the spectral law of radiation by black bodies which would conform to experimental data, Planck concluded that this law could not be deduced without assuming the quantum behaviour of light radiation and absorption. It was in this way that the far-reaching quantum laws were discovered.

Figure 18 illustrates the law of "black body radiation" for several temperatures. Light wavelengths are marked along the base in microns ($1\mu = 1000\ \mathrm{m}\mu$), and energy is marked off in relative units along the vertical axis. It will be seen from this diagram that the maximum of the spectral curve shifts towards shorter wavelengths with increasing temperature. This corresponds to the familiar gradual transition of a heated metal from the red hot state to white heat. The theoretical law governing the energy distribution in the spectrum of a black body has been confirmed by tests and experiments with all the accuracy which is now possible. A particular corollary of this law is that the product of the wavelength λ corresponding to the maximum of the spectral curve, by the absolute temperature T (i.e. the temperature $+273°C$) is a constant quantity

$$\lambda_{max} T = K = 2897{\cdot}18 \text{ microns/deg.}$$

Knowing the quantity λ_{max}, from the spectrum the temperature of a body can be determined by this formula.

We have considered the spectral distribution of light in connexion with the quality of sunlight. The sun is most decidedly a strongly heated body and therefore its spectrum must be similar to that of our own lamps and candles. In a poor spectroscope with a wide slit the

solar spectrum actually seems continuous and the measured distribution of energy in this spectrum forms a curve which is similar to one of the black body radiation curves (Fig. 18). From the shape of this curve and the position of its maxima, we can estimate the temperature of the sun's surface on the assumption that the sun's surface is similar

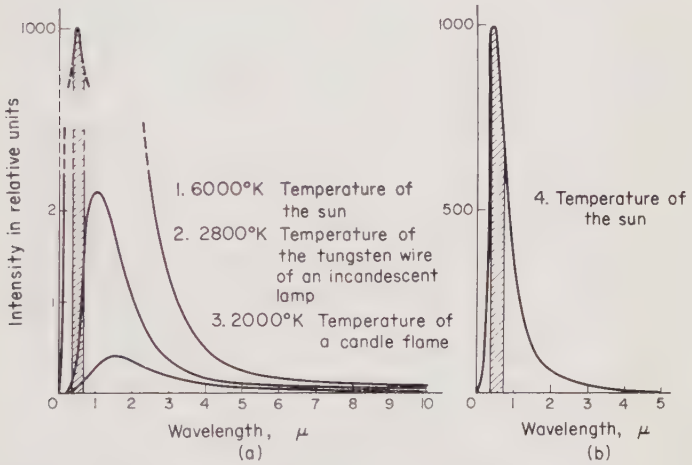


FIG. 18. Energy distribution in the radiation spectrum of a black body at different temperatures. Abscissa – wavelength in microns, ordinate – intensity in relative units. (Owing to the enormous difference in intensities, the curve for 6000°K cannot be represented to scale in Fig. 18*a*. Fig. 18*b* shows the complete curve on a smaller scale.) The shaded part refers to the visible region of the spectrum.

to a strongly heated black body. In this way the sun's temperature is estimated to be 6000°C. A closer figure is not required since different regions of the sun differ in temperature. Our eye is inferior to the poorest of spectroscopes in its ability to distinguish the quality of light. These rough estimates will therefore be sufficient when in the next chapter the properties of sunlight and eyesight are compared.

Physicists and astronomers study the sun by telescopes, spectroscopes and photography instead of by the eye. Properties of sunlight which elude the naked eye, and the distribution of light on the sun are disclosed by these means.

In 1802 Wollaston discovered a property of the solar spectrum

which for some reason was missed by Newton. The spectrum is interrupted with many thin black lines. These dark chasms on the bright background of the solar spectrum were later studied in detail by Fraunhofer and they are now known as the Fraunhofer lines. Table 1 gives the principal Fraunhofer lines for the visible spectrum. They are often used to indicate particular regions of the solar spectrum since they are always in the same position and serve as natural markers. The second column shows the wavelength in millimicrons, and the third the colour of the region in which the lines occur.

Table 1

Line	Wavelength (mμ)	Colour	Source
A	759·4	Red	Oxygen in earth's atmosphere
a	718·5	Red	Water vapour in earth's atmosphere
B	686·7	Red	Oxygen in earth's atmosphere
C	656·3	Red	Hydrogen on sun
D_1	589·6	Yellow	Sodium on sun
D_2	589·0	Yellow	Sodium on sun
E	527·0	Green	Calcium on sun
b_1	518·4	Green	Magnesium on sun
b_2	517·3	Green	Magnesium on sun
b_4	516·8	Green	Magnesium on sun
F	486·1	Blue	Hydrogen on sun
g	430·8	Violet	Calcium on sun
H	396·9	Violet	Calcium on sun
K	393·4	Violet	Calcium on sun

It has been seen that in a poor spectroscope the solar spectrum seems continuous and the energy distribution curve is regular and smooth. A detailed study of this curve shows that it is completely bitten into both in the visible and invisible regions (Fig. 19). These indentations are traces of the Fraunhofer lines. In the ultra-violet region the solar spectrum comes to an abrupt end, the actual boundary varying with the time of day and the season of the year. Rays of the sun with wavelengths shorter than 290 mμ fail to reach us. Shorter waves are absorbed by the ozone in the upper layers of the earth's atmosphere at altitudes up to about 19 miles.

How is the absence of certain colours from the solar spectrum explained? If a little table salt is added to a colourless alcohol or gas

flame, the flame turns bright yellow. Viewed through a good spectroscope, no continuous spectrum is seen, only two yellow lines side by side, the wavelengths of which coincide exactly with the Fraunhofer lines D_1 and D_2. The exactness is so great that it cannot be accidental. The difference is that the flame gives bright lines against a dark background, whereas the sun gives black lines against the brilliant background of the spectrum.

In the flame the salt decomposes into chlorine and sodium and the sodium glows. It is natural to suppose that the black D-lines on the

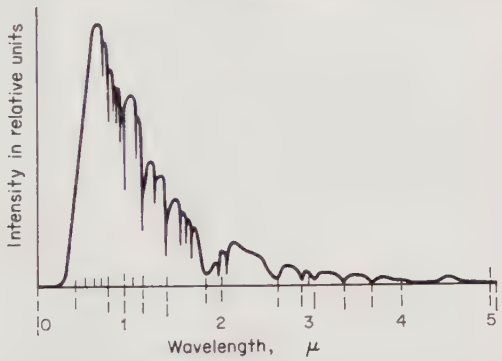


FIG. 19. Energy distribution in the solar spectrum. Abscissa – wavelength in microns; ordinate – intensity in relative units.

sun are also caused by sodium vapour. For instance, if in the path of a continuous spectrum, say of an electric bulb, we place a vessel containing vapour of metallic sodium, or a gas flame coloured by salt, the regions corresponding to the D-lines become weaker and the Fraunhofer lines are artificially produced on the background of a continuous spectrum. Thus sodium vapour is capable of absorbing and radiating the D-lines. To be more precise it should be said that the great majority of atoms of the sodium vapour are capable of absorbing light. But, having absorbed the light quanta of the D-lines, the atoms become energized, cease to absorb further radiation, and later dissipate the trapped energy in the form of light. In other words, strongly heated salt vapour contains some sodium atoms which absorb and other excited atoms which no longer absorb but glow. Similar luminescence can be excited in the vapour of any element in some way or other. The number of fine spectral lines can be very

large. This shows that the atom can be in a large number of states of excitation.

Atomic line spectra and continuous spectra of black bodies are governed by the quantum laws. This implies that the same quantum constant h holds for both. On the other hand, line spectra are expressions of the internal structure of the atoms which they represent. The structure of atoms is therefore governed by the quantum laws, like light. The quantum laws also manifest themselves in the spectra and structure of molecules. In a highly rarified gaseous state, molecules radiate "band" spectra. By means of spectral instruments these bands can be broken down into very narrow lines. The positions of these lines also conform to simple quantum laws. We again see common features between light and substance.

Let us return to the line spectra of atoms. Every element of matter has its own typical set of spectral lines. Their positions can be determined exactly and there is no danger of confusing one element with another. The chemistry of the sun and other heavenly bodies can therefore be studied on earth from their spectra. The vapours of elements constituting the sun's atmosphere leave their marks in the form of Fraunhofer lines on the continuous spectrum of the sun disk itself. The last column in Table 1 shows the elements to which the lines correspond.

Some of the Fraunhofer lines are produced by the absorption of sunlight in the earth's atmosphere. The majority of chemical elements in the earth's crust are also present on the surface of the sun. It is mainly the heavy elements such as gold, mercury, thallium, bismuth and radium which are absent.

Figure 20 compares the number of atoms of various substances in the earth's crust (x) with their atomic concentration on the surface of the sun (o). The logarithms of the relative quantities of the elements are marked off on the left, which means, for example, that the figure 5 corresponds to 10^5 atoms. It will be seen that the relative quantity of atoms of some of the substances on the surface of the earth and sun diverges very considerably. On the other hand such elements as sodium, silicon, calcium and strontium practically coincide. The absence of spectral lines cannot be taken to mean that the element is absent. The lines can occur in the ultra-violet region and therefore fail to reach the earth. The ultra-violet region of the solar spectrum is concealed from view on earth due mainly to the

ozone in the earth's atmosphere concentrated mostly in the stratosphere at altitudes of 20–30 km (12–19 miles).

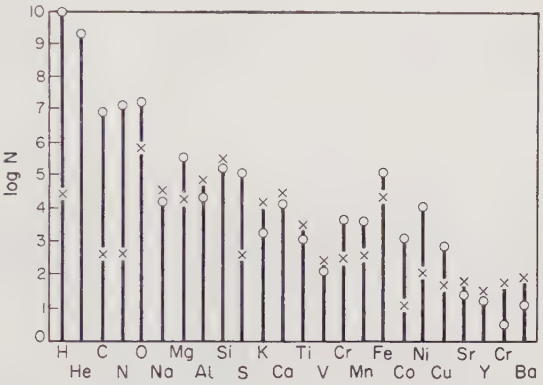


FIG. 20. Comparison of the mean relative number of atoms of various chemical elements on the surface of the sun and in the earth's crust.

After the Second World War the U.S.A. used captured German V-2 rockets to photograph the solar spectrum at altitudes above the

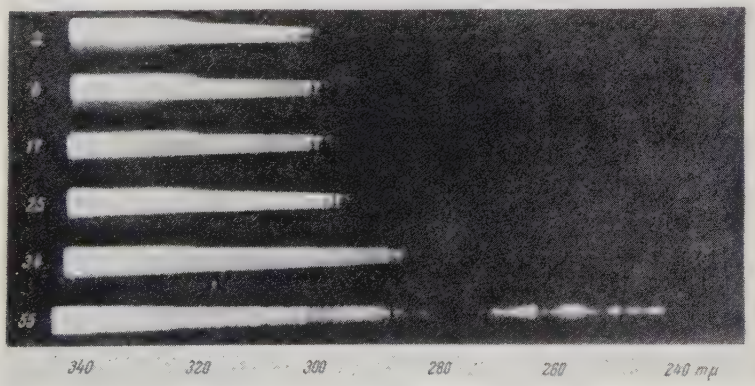


FIG. 21. The solar spectrum photographed from rockets at altitudes 2-55 km.

ozone layer. Figure 21 shows photographs of the spectrum taken by these rockets at various altitudes. The altitudes (in kilometres) are marked off on the left. Wavelengths are marked off in millimicrons

along the base. It will be seen that at an altitude of 25 km the spectrum begins to lengthen at the ultra-violet end. At 34 km the spectrum extends to approximately 280 mμ where it stops short. At 55 km a new wide frequency band is discovered extending to about 240 mμ. A dark region at 280 mμ still remains however; this corresponds to absorption by magnesium vapours.

Simple molecules such as OH, CN, CaH, H_2 and so on are to be found on the sun as well as atoms.

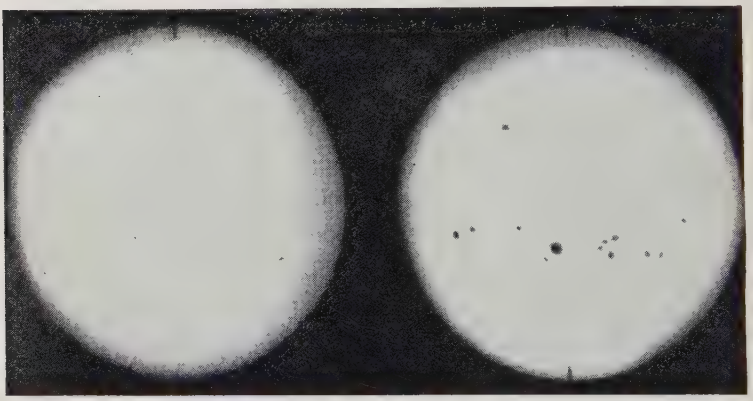


FIG. 22. The solar disk with the maximum (right) and minimum (left) number of sun spots.

The dimensions of the sun are enormous. Its diameter is about 1,400,000 km, i.e. 110 times greater than that of the earth, and its volume is 1,305,000 times greater. But the earth is much denser, the mean density of the sun compared with water being 1·406, whilst that of the earth is 5·6. The total amount of matter in the sun is 330,420 times the quantity in the earth. The total quantity of matter in the sun is 2×10^{27} metric tons (i.e. 2 with 27 zeros), but it is difficult to grasp the significance of such a large figure; if, however, the sun were to lose weight at a rate of 1000 million tons per second, it would take over 30,000 million years for half the sun to "wear away"!

This huge accumulation of matter is only known to us from its surface. Nothing is known of the internal character of the sun and only guesses can be made. The surface of the sun, however, is far from homogeneous. When we speak of the energy distribution of sunlight and its temperature, we always have in mind a rough average value.

The apparent journeyings of the sun across the sky are accompanied by an equally apparent change in energy distribution. On rising and setting the sun appears to be red, its rays having to penetrate a much thicker layer of atmosphere than when it is at its zenith.

There are almost always spots on the surface of the sun, mainly in the equatorial regions (Fig. 22). These spots are sometimes so large that they can be seen by the human eye through a smoked glass. In Chinese chronicles, observations of sun spots by the naked eye date as far back as 28 B.C. In 1858 a spot was visible on the sun 230,000 km

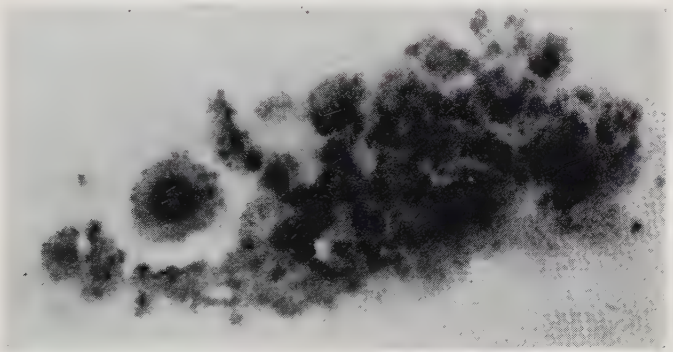


FIG. 23. A group of sun spots.

in length, i.e. 18 times greater than the diameter of the earth. The spot occupied 1/36 of the total visible surface of the sun. The spots vary in shape, with a dark nucleus in the centre and a lighter border (Fig. 23).

Spectroscopic investigation reveals the presence mainly of hydrogen and calcium vapour in the region of the spots. Immense whirlwinds and cyclones, consisting sometimes of flows of electronically charged particles, envelop the spots. The resulting electrical currents are accompanied by enormous magnetic fields which cause changes in the spectral lines. These spectral changes permit the detection of solar whirlwinds.

The number of sun spots varies cyclically; the length of a cycle is about 11 years. Figure 24 confirms this periodicity. The years are marked off along the base and the number of sun spots along the vertical axis. The curve covers almost two centuries from 1749 to 1947. The sun spot cycle is perfectly clear. This law of solar activity

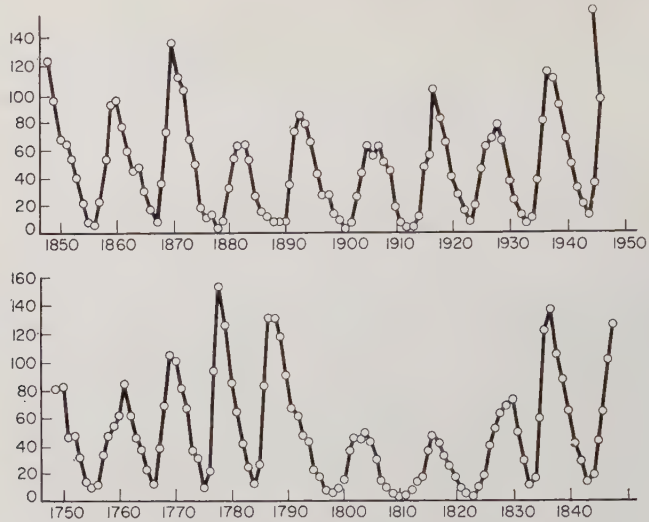


FIG. 24. The 11-year sun-spot cycle.

is undoubtedly of very great importance for life on earth. Figure 25 again shows part of the same curve from 1836 to 1926, but it is compared with the curve for magnetic disturbances on the earth in the same years (the upper curve). The two curves are obviously related. Thus, besides gravitation and light, there are other relationships between sun and earth. It is known for instance that streams of

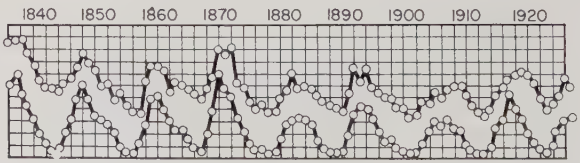


FIG. 25. The sun-spot cycle in relation to magnetic disturbances on earth (upper curve).

negatively charged particles (electrons) are constantly streaming from the sun to earth. These electrical streams are deflected by the magnetic poles of the earth toward the polar regions and produce changes in terrestrial magnetism as shown in Fig. 25. On the other hand, penetrating the upper rarefied layers of the earth's atmosphere, the electrons compel the gases in those layers to glow. This explains the

phenomena of the northern and southern lights. The frequency of the aurora in the polar regions follows the same cycle as the sun spots and magnetic disturbances.

Variations in the frequency of sun spots have a considerable effect on the weather and therefore on vegetation and all life on earth.

FIG. 26. Cross-section of the trunk of a pine tree showing how the thickness of the rings varies with an 11-year cycle.

Figure 26 shows a photograph of a cross-section of the trunk of a pine tree from which it will be seen that the thickness of the annual rings varies with the 11-year cycle corresponding to the periodicity of the sun spots. Figure 27 shows a sun-spot curve for the years between 1830 and 1910 which is compared with the mean growth of trees in several European countries. The same relationship exists between these curves, although the pattern is slightly complicated by other factors which are independent of the sun spots. There is, however, no doubt that the sun spots are an important factor in life on earth. The outer shell of the sun, which is all we see in normal conditions, is called the photosphere. This covering has a granular

structure which is particularly clear if the sun disk is photographed in the monochromatic light of an individual spectral line, e.g. of hydrogen or calcium (Fig. 28). The granules of various shapes and

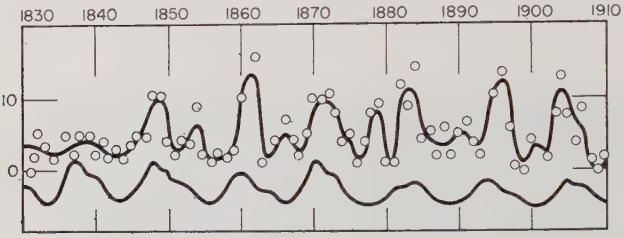


FIG. 27. The sun-spot curve (lower curve) in relation to the mean rate of tree growth in various European countries.

sizes evidently correspond to clouds of vapours and gases floating in the photosphere. If we look down from the top of a mountain on a

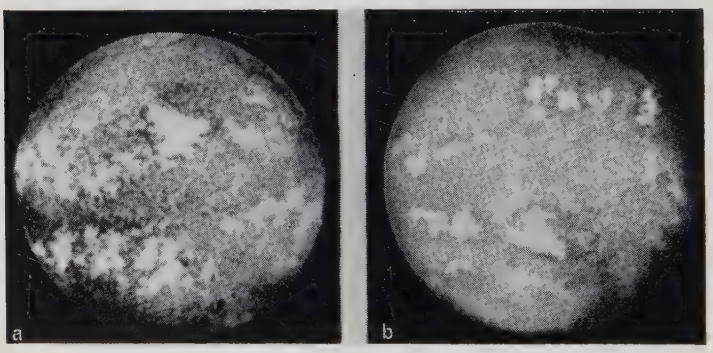


FIG. 28. Spectrogram of the sun taken in the light of the calcium (A) and hydrogen (B) lines.

cloud (Fig. 29), we see the same type of granular structure. Some parts of the photosphere glow particularly brightly; in these "faculae" the lines of calcium are most pronounced.

During a total solar eclipse it is possible to see the photosphere in detail (we see it as if in cross-section, Fig. 30). The photosphere is surrounded by a thin red layer called the chromosphere into which the faculae penetrate from the photosphere. The thickness of the chromosphere is about 6200 miles. Colossal fountains of luminous gas spring from it to heights of 200,000 miles. These are called

FIG. 29. View of a cloud from the top of a mountain.

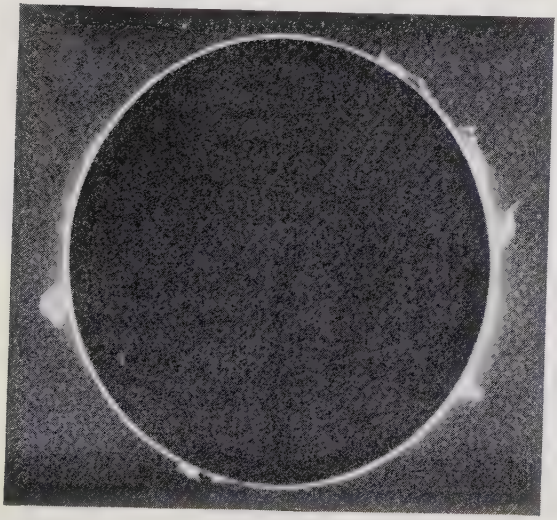


FIG. 30. The solar chromosphere with prominences.

prominences. Prominences are mainly of two types, the sunspot type and the eruptive type. In the former the main source of light is hydrogen, as in the chromosphere itself, but in the eruptive prominences there are pronounced metallic vapour lines as well as hydrogen. In recent times astronomers have had at their disposal new methods for observing prominences at any time, not only during eclipses. The sun disk is blotted out in the telescope by a dark disk made from high quality glass without dispersing bubbles or knots. Good light filters are used which only pass a narrow part of the spectrum. In the last 10 years improved light filters have been developed abroad and in the U.S.S.R. which transmit practically only one narrow spectral line. As a result it is possible to film the prominences and so reveal hitherto unseen features of solar eruptions.

Between the photosphere and the chromosphere there is a very narrow *reversing layer* in which the principal Fraunhofer lines apparently originate.

During a total solar eclipse the amazing phenomenon of the *corona* can be observed by the naked eye (Fig. 31). The corona stretches out from the sun for millions of miles and is usually of a radial structure. Sometimes the rays are uniformly spaced round the sun, but in other cases the corona is elongated in particular directions. Three spectra can be distinguished in the cross-section of the corona. The brightest is the continuous spectrum of the corona's inner ring. In this spectrum there are no Fraunhofer lines; the nature of this part of the corona is still a matter of guesswork. It is usually attributed to the scatter of the sun's rays by an atmosphere of electrons. It has, however, not yet proved possible to develop this idea consistently to its conclusion in conformity with all known facts. The second spectrum is also continuous, but with Fraunhofer lines; it is attributed to the reflected light of the photosphere (the reflection possibly being caused by the comparatively cool dust particles at some distance from the sun). The third spectrum is a line spectrum and corresponds to the luminosity from atoms. It may be supposed that this third spectrum arises from the fluorescence of vapours under the influence of solar light. This is indicated by certain features of the polarization of the spectrum. The sun is surrounded for several million miles by a layer of substance in a rarefied state, partly in the form of vapour and partly in the form of dust. This dust and vapour may be repelled from the sun by electrical forces and the pressure of light. However,

in many respects the solar corona still remains an inexplicable phenomenon. It may be for instance that some part of the luminosity of the corona is caused by a process of "self-dispersion" as a result of the interaction of intensive light beams near the sun. The present-day theory of light allows for such a possibility.

FIG. 31. Illustrations of solar corona taken during total solar eclipse in September 1937. The original photographs were taken through a Polaroid in two mutually perpendicular positions, as indicated on the illustrations. The difference in the illustrations shows that the corona light is polarized.

We will conclude our brief outline of the phenomena taking place on the surface of the sun with a few words about the sun's energy. This energy is distributed throughout the spectrum in the invisible and visible regions. About 40 per cent of all the energy occurs in the visible region.

Imagine the earth to be devoid of atmosphere. Using direct measurements of the energy of sunlight, it can be calculated that for sunlight arriving at right angles to the surface of the earth, the

energy received per square centimetre on the earth's surface is on the average two calories per minute, or 0·003 calories per second. But the part which is absorbed by the atmosphere has to be subtracted.

Knowing this figure, called the *solar constant*, no difficulty arises in calculating the amount of energy radiated by the sun per second. Assuming that the radiation of the sun is the same in all directions, we calculate the surface of a sphere with a radius of 150,000,000 km (the distance between the sun and the earth) and multiply this area, expressed in square centimetres, by the solar constant, i.e. by 0·003 calories. This calculation gives a figure of approximately 10^{26} calories per second (i.e. figure 1 with 26 zeros after it). This calculation will convey nothing to the average reader and indeed, even the notion of a calorie is rather technical. We will therefore look at the matter in a more illuminating way.

Physicists have discovered that energy is always equivalent to mass. The first indication of this fact was the pressure of light on a body discovered by Lebedev. The refined and exceptionally difficult experiments carried out by Lebedev proved that light, being incident on a dark plate which completely absorbs it, exerts pressure on the plate with a force to E/c, where E is the energy of light absorbed per second and c is the speed of light. If the plate is not black, but a mirror which completely reflects light, the pressure is twice as much. Lebedev, by many years of experiment also demonstrated that light exerts pressure on gases as well as solids. This circumstance is of major significance in the present-day theory of solar phenomena.

It follows from the laws of mechanics that to stop a flow of light or even water which exerts pressure for a period of time t, it is necessary to balance it by a force F defined from the relationship $Ft—mv$, where mv is the product of the mass m conveyed in the flow with its velocity v, this product being called the momentum. Thus the force of the flow F is equal to the change of momentum per second, i.e. $F = mv/t$. In the case of a light flow $v = c$ (the speed of light). Equating this expression to Lebedev's expression for the magnitude of light pressure, we find that $mc/t = E/tc$, whence $mc^2 = E^*$.

This formula gives the mass m equivalent to the energy E of light. It was deduced here by applying the laws of mechanics to Lebedev's

* This analysis is slightly different from that given by the author who used the same quantity to denote the energy of light as well as the *power* of light, which might confuse the reader—[*Russian editor*].

optical measurements and at first sight it only seems applicable to light. Einstein was the first to show that the equation

$$mc^2 = E$$

is universal and should hold for any type of energy. Einstein's conclusion is continually obtaining confirmation in physics, particularly from the development of nuclear physics, and it must now be regarded as one of the most important relationships in all science.

Using this formula, the energy radiated by the sun per second can be re-calculated in terms of mass. The figure of 10^{26} calories per second is found to be equivalent to about 5,000,000 tons *per second*. This mass, though enormous in itself, is infinitesimal compared with the sun. We have seen that it would take 30,000 million years for half the mass of the sun to "wear away" with mass transfer at the rate of 1000 million tons per second, but it would take 6 billion (million million) years at the rate of 5 million tons per second.

Likewise, the rate at which energy reaches the earth can be re-stated in terms of mass. Here it must be borne in mind that only half of the earth's surface is illuminated at any one time and that the solar constant refers to rays at normal incidence. As a result we get a modest figure of about $4\frac{3}{8}$ lbs per second (the figure of 2 kg per second is easier to remember).

These calculations give a good idea of the energy radiated by the sun, but they are important in another respect in that they emphasize that it is the sun's mass and its practically inexhaustible energy which reaches us on earth. How are such masses as the sun formed and where is the source of the continuously radiated energy? Such masses are probably attracted to solar centres by universal gravitation. But the mass of the sun appears to be about the outside limit; there are other accumulations of matter ten times greater than the mass of the sun, but astronomers know of no continuing growth. What is the explanation for this limit?

In the accumulation of mass by universal gravitation, colossal pressures arise inside the heavenly bodies and enormous temperatures are developed which must reach tens of millions of degrees. Heated far beyond white heat to the heat of X-ray light, the inside of a star emits (according to Planck's law) extraordinarily large amounts of radiant energy from the core outward. This internal light presses outward on the star's mass. Light pressure thus counteracts the

force of gravitation. This counteraction naturally cannot exceed the gravitation which calls it forth. But the light pressure is supplemented by the centrifugal force due to the rotation of the star. When the sum of the light pressure and the centrifugal force is equal to the force of gravitation, the mass of a heavenly body can no longer grow. Theoretical calculations indicate that masses of the order of the sun's mass are the maximum possible in the universe. Such is the partial answer of astro-physicists to the question of the origin of the sun's mass.

But how is the sun's energy replenished? At one time it was thought that the flow of meteors incident on the sun may be sufficient to compensate the radiation loss since their mass each year is approximately equal to one hundredth part of the earth. It has also been pointed out that the contraction of the sun's diameter by 82 yards per year should develop enough heat to compensate transfer. In this way we can anticipate the existence of the sun in its present form for at least another 100 million years. This period, however, is quite insignificant; geologists and astro-physicists predict thousands of millions of years at least. Such longevity cannot be explained by the foregoing suggestions.

The source of solar and stellar radiation must be sought in quite different directions, in the reserves of energy discovered by the new branches of physics. The relationship between energy and mass about which we have just been speaking indicates in general form that any accumulation of mass can be regarded as equivalent to energy. Every ounce of mass represents immense energy, a quantity which can be calculated by multiplying the mass by the square of the speed of light. One gram of mass is equal to 20 million million calories. It would be necessary to burn over 20,000 tons of coal to generate the same amount of energy.

We have mentioned coal as a simple example of a source of thermal energy. It is instructive to consider this example a little more closely. A piece of coal is an inert mass which from the mechanical point of view is very little different from stone. For hundreds of thousands of years it lay in its inert state until, finally, it fell into the hands of man who thought of converting its latent energy into an accessible form of heat by burning it in oxygen*. This discovery was a very important

* The author has in mind not the latent energy of the coal, but the energy of the system (coal + oxygen), liberated on transition of this system to carbon dioxide (combustion)—[*Russian editor*].

event in the history of mankind. It meant, as we now know, the liberation of the latent chemical energy of coal. But people of our day have been made witnesses of another exceedingly important event the beginning of the conquest of nuclear energy. In man's hands the mastery of nuclear energy will undoubtedly mark a decisive stage in the development of engineering which will allow the solution of economic problems which could not hitherto be tackled. Atomic energy, liberated in the appropriate processes, is immeasurably greater than the energy obtained by burning coal. Yet both these processes are essentially the same in that the latent energy of matter is used in an accessible form.

In what way can the latent energy, equivalent to mass, be converted into accessible forms of light and thermal energy? Modern physics can point to three methods of conversion. The first method is to convert particles of substance such as protons into light. In the chapter on Light we mentioned the conversion of light into matter, the conversion of the light quantum into the electron and positron. But the reverse process is equally possible. The probability of it taking place in normal conditions is extremely small, but inside the sun where the density and pressure are enormous and the temperature reaches millions of degrees, such processes may take place much more frequently. As a result of these processes the entire mass of particles which disappear manifests itself in the form of light energy. To avoid a common mistake, it is important to point out that the mass does not disappear, it does not change into energy, as is sometimes said; the mass remains in the form of the mass of photons, and only the equivalent energy is converted from its latent form into the accessible form of luminous energy.

The second method of converting the latent energy equivalent to mass into accessible energy is by nuclear disintegration. An old well-known example is the disintegration of the radium atom. But this process takes place extremely rarely in nature and large amounts of energy are not produced. An important step forward in the utilization of nuclear disintegration as a source of energy was the discovery of the fission of the uranium atom 235 under the action of slow neutrons. This uranium isotope (235 is its atomic weight) constitutes 0·7 per cent of ordinary uranium. The main advantage of this process is that it sets up a chain reaction. Each nuclear fission gives rise to new neutrons which in their turn cause further fission. A chain of dis-

integrating nuclei is produced and a considerable amount of energy is released at each link. Modern atomic engineering is based on this phenomenon. But evidently this process is of no importance to the sun; reasonable theoretical considerations indicate that the heavy atoms such as uranium and others do not exist inside the sun.

The third method of transmutation is the opposite of that just considered in that it consists of the synthesis of atomic nucleii and not in their disintegration. This has long been known from comparison of atomic weights. For example, the atomic weight of hydrogen is 1·0080, whilst that of helium is 4·003. But since helium is built up of four hydrogen atoms, we should expect its atomic weight to be $4 \times 1{\cdot}0080 = 4.032$. Comparing this quantity with the atomic weight of helium, we get a marked difference $4{\cdot}032 - 4{\cdot}003 = 0{\cdot}029$.* The only explanation for this difference is that the formation of the helium nucleus from the hydrogen nuclei is accompanied by the transformation of a considerable amount of substance mass into radiation mass and other forms of energy. This energy is enormous: the conversion of 1 gram of hydrogen into helium generates 5 million times more energy than the same gram of hydrogen when burned in the presence of 8 grams of oxygen to form water.

There are impressive grounds for supposing that it is this process of formation of helium nuclei from hydrogen nuclei (protons) which forms the basis of solar energy. The accelerator, or catalyst, is in this case probably the carbon nucleus. But the problem cannot as yet be regarded as finally solved; it is only clear that there are several possibilities why this should be so. There is no doubt, however, that the light of the sun received by us on earth is the result of the operation of an enormous machine which has been releasing atomic energy inside the sun for billions of years.

In our laboratories on earth we are unable to recreate the enormous pressures which must exist inside the sun. One thing is certain, radiation must lead to a reduction in solar mass. The sun is, as it were, burning itself out, but not in the usual chemical sense in which the products of combustion remain a useless inert mass; its mass departs into the universe as an active form of energy, luminous radiation; as we have seen, the light received on earth per second from

* More exactly, the nucleus of helium is constructed from two protons (the nuclei of hydrogen) and two neutrons. In accordance with this, the difference in atomic weight should be 0·030—[*Russian editor*].

the sun is equal in mass to $3\frac{1}{2}$ pints of water. But well we know that the whole world lives on $4\frac{1}{2}$ lbs of light, and that $3\frac{1}{2}$ pints of water is a trivial amount.

The rays of the sun carry its mass with them. Light is not an incorporeal envoy of the sun, but the sun itself, a part of it, which comes to us in a perfectly transmuted form of energy.

THE HUMAN EYE*

The eye owes its existence to light. From among the indifferent auxiliary organs of animals, light calls forth an organ which would become akin to it; and thus is the eye born in light, for light, in order that the inner light meet the outer.

Goethe

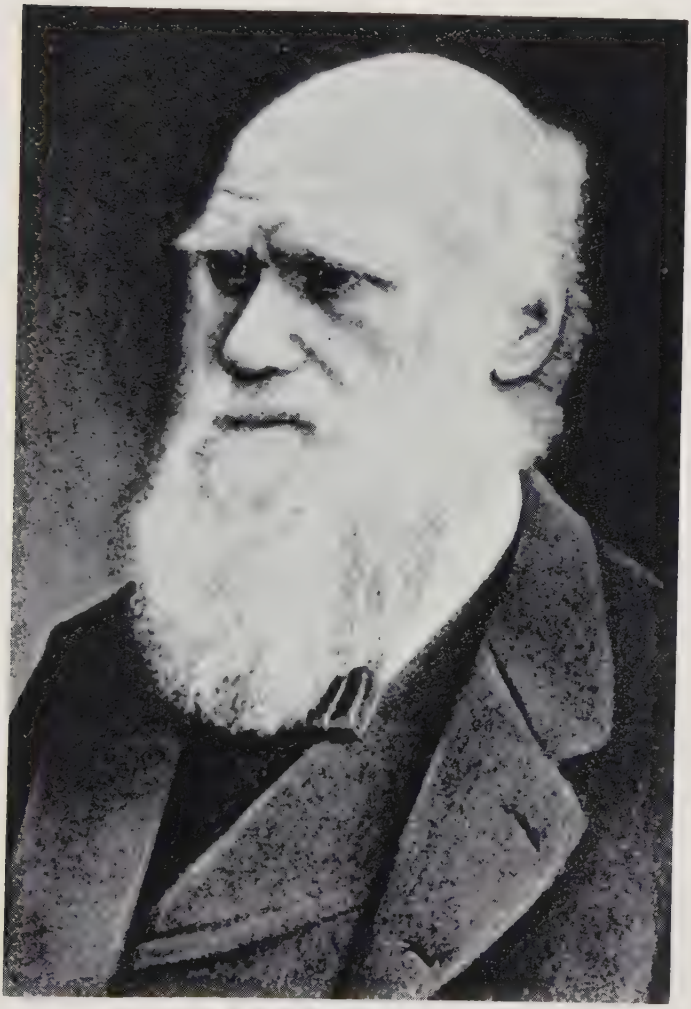
Thy rays create the eyes of all thy creatures.

Lesser Hymn to Áten

No living creature has a more faithful or potent protector than the eye. To see is to tell friend from foe and know the lie of the land. The other senses do the same, but comparatively poorly. The tactile senses and feeling of warmth provide information about the external world only by direct contact; hearing and smell, which are not so restricted, provide insufficient information about distance, direction and shape. Such expressions as "obviously" and "we live, we see" imply that if something can be seen it is authentic. A modern physicist can convince others of the reality of atoms because he can point to their paths; persons who formerly denied the existence of atoms constantly argued that no one could see them. This is the meaning of the saying by Anaxagoras "Vision is the appearance of the invisible"; the invisible world becomes a reality through vision.

The functions of an ideal eye as a physical organ are quite clear.

* Only a few slight changes have been made in this chapter in accordance with the terminology of physiological optics. Sometimes the author departs from strict scientific terminology. This may have been done intentionally owing to the complexity of this terminology which is unsuited to a work of popular science. We have therefore mainly confined ourselves to the correction of slips of the pen and misprints.—[*Russian editor*].



CHARLES DARWIN (1809–1882).

Light is received from surrounding objects and the eye indicates the direction of the rays, their energy, spectral composition and polarization. Each point of an object should be perceived individually. Ideally, the combination of these sensations in the brain centre should recreate a replica of the radiating surface with all its optical features. A correct three-dimensional image must be produced and the brain should be supplied with correct information about shape, size and distance. The brain should also be able to adjust the information according to requirements.

As we shall see, the human eye comes quite close to this ideal. How is it that an auxiliary organ can solve difficult optical problems more perfectly than a scientist with all the latest physical knowledge and techniques?

This question is best answered by Darwin's theory of evolution. The human eye is the result of an exceedingly long process of "natural selection", the result of changes under the influence of environment and the struggle for existence for better adaptation to the external world.

The factor of heredity guarantees the retention of biological properties if they correspond to the environment and increase vitality in the struggle for life. The diverse influences of the environment create differences in individuals which in some cases give them particular advantages over others. In this process of "natural selection" it is the fittest and strongest which survive and multiply.

In the world there are all kinds of eyes; not all are perfect, but to a certain extent they do what is required, even though they may seem "comical" to man.

Various types of eye are shown in Fig. 32, "devices" for the visual perception of the external world. Figure 32*a* illustrates the "eye" of a single-cell organism. A spherical lens *l* is accommodated in front of a sensitive substance. It is of course impossible in this case to speak of an apparatus for receiving images. The very small size of the lens and retina is such that severe diffraction inevitably occurs, with the result that the image is greatly distorted. Figure 32*b* illustrates the visual organs of a dew worm. Here there is no eye; the entire surface of the worm is light sensitive; the visual cells are connected to nerve fibres which are distributed uniformly over its body; it is impossible to speak of an image in this case. Figure 32*c* illustrates a primitive solution in which the light is picked up by a visual cavity something

akin to the ear; such a device can tell the direction of a luminous body approximately, but no more. Figure 32*d* shows a more advanced solution of the problem in shell-fish, a live camera-obscura with a small aperture *p* and an internal light-sensitive cavity *r*. The last four examples in Fig. 32*e*, *f*, *g*, and *h* show improved solutions using

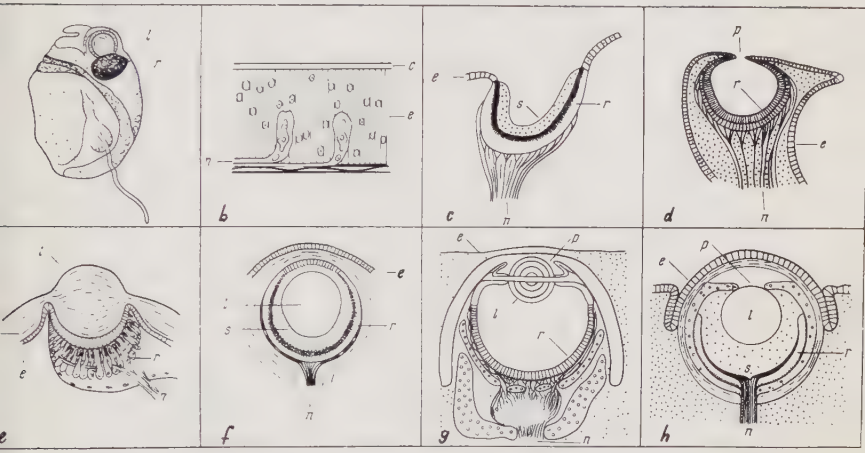


FIG. 32. Various methods of visual perception in the animal world.

a – a single-cell organism *Pouchetia Cornuta*; *b* – light-sensitive cells over the skin of a dew worm; *c* – a mussel's visual organ in the form of a cavity, *Patella bivalve*; *d* – eye in the form of a camera-obscura, mollusc; *e* – the eye of the scorpion Euscorpine with concentrating lens; *f* – the eye of the *Murex* snail; *g* – the image-producing eye of a Cephalopod *Loliga*; *h* – the eye of a vertebrate; *c* – cuticle; *e* – epithelium; *l* – lens; *n* – nerve fibres; *p* – pupil; *r* – retina; *s* – internal transparent medium.

lenses. For the scorpion this is still a very rough instrument (Fig. 32*e*); instead of a lens, it has a sphere which is close to the sensitive layer *r*. This is reminiscent of the glass spheres which, according to legend, were used in antiquity as kindling glasses, or the Leuwenhoek microscope with "lenses" made from drops of honey. Figures 32*f*, *g* and *h* show the gradual transition to an eye similar to that of a human being from the snail and cephalopod to the vertebrates. The problem is not solved in the same way for all the various vertebrates. Figure 33 illustrates the eyes of several nocturnal (opossum, mouse and

lynx) and diurnal animals (puma, dog, camel, man, pigeon and chameleon). It is immediately apparent that the problem is solved optically in many different ways.

From the point of view of adaptation to environment, it is very interesting and instructive to consider the eyes of fish which live at great depths where sunlight hardly penetrates. It might be supposed that such fish would simply have no eyes at all; they might not need eyes. But in fact this is not the case. The majority of deep-water fish

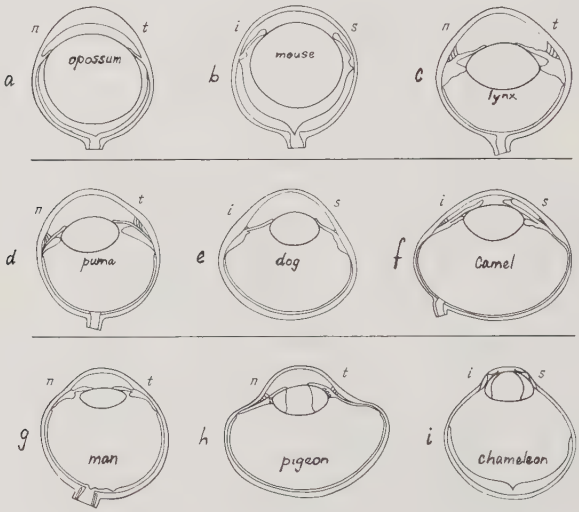


FIG. 33. The eyes of various vertebrates in cross-section.

do have eyes and moreover (relatively) they are the largest among the vertebrates. In this respect (or largely for this reason) their eyes are apparently the most sensitive in the animal kingdom. How can this fact be reconciled with the absence of light in the depth of the ocean? In the first place the answer is that feeble traces of sunlight do penetrate to considerable depths in the ocean. But the advantages of visual perception in the search for food, reproduction of the species and in the struggle for existence are such that it is much more worth while to increase the sensitivity of the eye to light than to follow the line of least resistance and doom the eye to extinction.

But it is not only the feeble traces of light which penetrate into the depths of the ocean which explain the eyes of the creatures which

live there. Deep-sea fish are themselves capable of producing light, illuminating their surroundings and becoming visible to other seeing creatures. They have therefore developed luminescent organs which are situated near the eyes, or on other parts of the body. Figure 34 shows the *Photoblepharon palpebratus* and the *Anomalops katoptron* which are

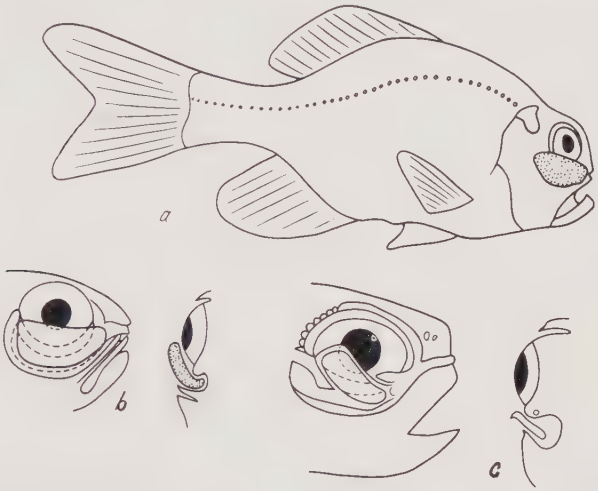


FIG. 34. Fish with luminous organs connected to their eyes.

a – *Photoblepharon palpebratus*; *b* – its head in profile and in cross-section, showing its light-producing organ and the screen covering it; *c* – head of an *Anomalops katoptron* in profile and cross-section. The light-producing attachment and the cavity into which it can be withdrawn is also shown.

fishes which have a luminous tissue (marked on the diagram with a dotted line) side by side with the eye. The luminescence of this tissue is produced by oxidation. It serves as a small beacon which lights them on their way. Such beacons can, however, be dangerous for a fish since it reveals it to its enemies. Both the fishes illustrated in the diagram have therefore acquired "eyelids" for hiding the luminescence if necessary. The first fish does this by moving out a special dark shield, whilst the second withdraws the tissue into a protective shield (Fig. 34*c*). Such luminescent "lamps" are by no

means a rarity among deep-water fish. Over 90 per cent of all fish living at great depths possess such organs.

In this book we are primarily concerned with the human eye since the relationship between the eye and the sun is the theme of the book. It is also the case that only the human eye has been studied at all profoundly, though much remains unknown even here.

Consider first the spatial problem. How is a geometric replica produced in the eye and how does the eye estimate distance? The only spatial characteristic of light which a light-sensitive organ can use is the direction of the rays. For growing plants light is not only the herald of surrounding objects, but also the source of life itself. Leaves

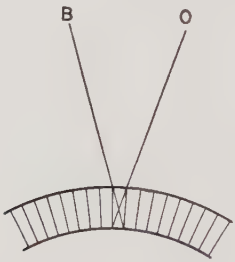


FIG. 35. The method of vision for various insects.

are drawn to the sun and the sun's rays guide them. They grow more on the sunny side and arrange themselves so that they do not shut each other out from the sun. Very many plants and flowers turn and follow the sun throughout the day. Fields of sunflowers follow the sun in formation as if by command. The same attraction to light, phototropism (sometimes negative) is also displayed by many kinds of microbes, infusoria and other simple organisms. This reaction to light, to the direction of its rays and energy, can be regarded as a primitive form of vision.

Some insects have organs for estimating the direction of rays and reproducing visual images like that shown in Fig. 35. Small cones are arranged in a mosaic pattern, like honeycombs on the retina, formed by nerve endings. The walls of these cones are coated with a dark substance which absorbs light, like the black matt varnish on the inside walls of binoculars. Only rays between the lines *B* and *O* can reach the bottom of this conical cell. The rays from another section reach the bottom of another cell. As a result a rough mosaic picture of the

object is formed on the retina, by which the insect can recognize the shape of the object.

Just as cameras with objective lenses have superseded the camera-obscura in photography, so has biological evolution led from the mosaic of tubes to the lens apparatus of vertebrate animals. A cross-section of the human eye is shown in Fig. 36. The eye is almost spherical in shape, its diameter being about 16 mm in a new-born child and about 24 mm in an adult; the eyeball of a horse is about 51 mm in diameter and that of a rat is about 6 mm. The outside of the eye is covered with a thick membrane (the white of the eye called the sclera); its front part (the cornea) is transparent, convex and

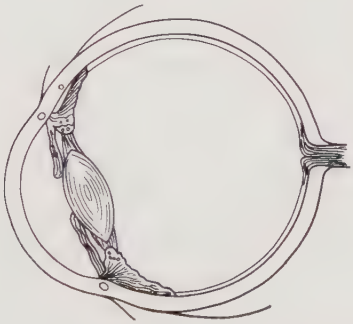


FIG. 36. The human eye in cross-section.

about 0·5 mm thick. Behind the cornea is the anterior chamber of the eye which is separated from the posterior chamber by the crystalline lens. Directly in front of the crystalline lens is the iris, with an almost circular aperture (pupil), which limits the cross-section of a beam entering the eye. The anterior chamber and the crystalline lens are about 3·6 mm thick. The anterior chamber is filled with a transparent liquid, and the posterior by a transparent glass-like substance; the index of refraction of both substances is approximately the same as that of water (1·336). The inside surface of the white of the eye is lined by the vascular tunic which can be regarded as a branch-like structure of blood vessels forming a membrane and feeding the eye. The light-sensitive retina is on the inside surface of this membrane, the retina is composed of two layers, an outer or pigmented layer and an inner or neutral layer, and is an extension of the optic nerve.

The crystalline lens is composed of layers. Its convexity can be

varied by the muscles of the iris; the maximum index of refraction in the layers of the lens is 1·41. Pictures are produced on the retina of the eye in exactly the same way as on a camera film. The ability to vary the convexity of the lens (called accommodation) makes it possible to focus the eye and so obtain a distinct picture on the retina. Children can see objects distinctly at distances from 7–10 cm from the eye. The normal eye of an adult begins to see objects distinctly at 14 cm. In old age the faculty of accommodation usually deteriorates considerably.

Such irregularities as short-sightedness and long-sightedness can be corrected by artificial lenses (spectacles) using diverging or collecting lenses. The image on the retina of the eye is far from perfect. It is exact only if the picture is small and if it lies on the axis of the eye. It should, however, be mentioned that "spherical aberration" is well corrected in the human eye. This is helped considerably by the fact that the inner layers of the crystalline lens are more dense than the outer layers.

The quality of an image improves when the iris contracts the pupil of the eye. This can easily be verified by persons who suffer from long-sightedness. In bright illumination they will see nearby objects (25–40 cm) more clearly and distinctly. In such light the pupil contracts and consequently the angle of opening for rays entering the eye is reduced. A long-sighted person can also read comparatively small print at short distances without spectacles if he lightly clenches his fist and looks down the hole.

These disadvantages are to some extent compensated by the ability to roll one's eyes. The eye can be rolled more than 80 degrees in the vertical and horizontal directions so that large objects can be scanned very quickly.

The approximately plane picture on the retina gives an idea of the dimensions and distance of an object as well as its shape, even if only one eye is used. The explanation may well be that we have acquired sufficient experience in estimating dimensions and distance by two eyes such that when using one eye we can draw on that previous experience. The ability to vary the convexity of the crystalline lens is also undoubtedly of value since we unconsciously sense its tension and estimate distance by that. A substantial role must surely also be played by the unconscious movements of the eye. A number of pictures of objects are received from different points of view in a

short period of time and their comparison must make it possible to estimate distance.

However, impressions of space with one eye are not at all reliable. Take a pencil in each hand, close one eye and try to make both points meet head on. In the majority of cases this attempt is not successful first time. Yet, if both eyes are used, the experiment never fails if we try hard. In directing the axes of both eyes at a particular

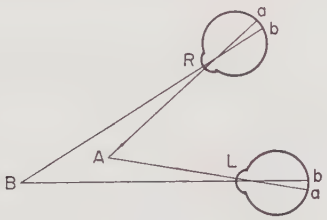


FIG. 37. Binocular vision.

object, we set them at a certain angle (Fig. 37). The instinctive assessment of this angle serves as a measure of distance within fairly wide limits. It is very important to bear in mind that our subjective visual impressions and images are adjusted automatically in our brain. One of the most important instances of this intervention by the brain is the rectification of images on the retina since the images produced

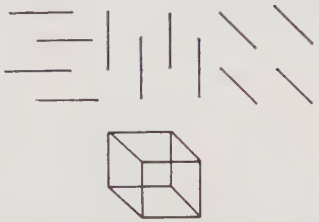


FIG. 38. Perception of perspective. The twelve lines at the top of the diagram seem to lie in the same plane. In aligning them at the bottom of the diagram the cube appears to be a three-dimensional form.

by the crystalline lens are upside down. The correcting role of the brain is very great in spatial perception. Figure 38 shows a set of lines which go to make a cube and the actual cube. The latter produces a three-dimensional impression. This is obviously the result of the brain working. It is on this basis that correct perspective is obtained

in drawings. For an object to seem further away, it is ·essary to draw it smaller in proportion. If a person is supposed to be standing twice the distance away from the spectator, he has to be drawn half the size. Two persons thus depicted seem to be equal in height, but twice the distance apart.

Figure 39 shows the results of experiments carried out by Gullway and Boring into the relationship between the apparent size of an object and its distance from the observer. A luminous disk was used as the object. Its angular dimensions were held constant throughout the experiments, but the distance between it and the observer was varied between 3 to 36 metres. Its apparent size was compared with

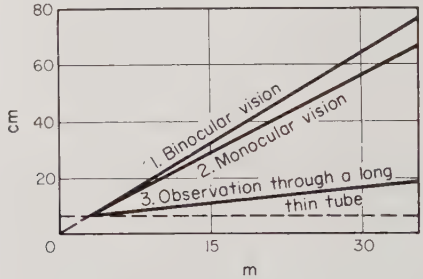


FIG. 39. The experiment of Gullway and Boring.

another luminous disk at a fixed point 3 metres away from the observer. The diameter of this disk was adjusted so that it was kept exactly equal to the moving disk. If the brain did not make automatic corrections to the dimensions of the image on the retina of the eye, it was to have been expected, in view of the constant angular dimensions of the moving disk, that we would obtain the horizontal straight line which is hyphenated in Fig. 39, where the distance is marked off along the base in metres and the apparent size in centimetres along the vertical axis. Yet this was not the case at all. Sloping lines were obtained, whether the disk was observed by two eyes, one eye, or through a long thin tube. The slope of these lines decreases as more surrounding objects are eliminated from sight.

This quantitative study corresponds to the well-known fact that relatively nearby objects seem to be the same in size even though they are moving away from us. It is only in the case of very distant figures and objects that we become conscious of a reduction in size. This is

quite app t if we look down from a high tower. The environment is of very great importance in the ability of the brain to introduce corrections to the physical image of objects on the retina of the eye. If the environment is eliminated, the result begins to be purely physical. The simple physical images on the retina of the eye are thus automatically corrected, unbeknown to us, before we perceive them. This psychological correction is naturally of very great bio-

FIG. 40. Photograph of a man lying down. An example of optical correctness without psychological adjustment.

logical value. A living creature needs a correct idea of the objects which surround him; he does not need correct optical images. Figure 40 shows a close-up of a man lying down. Optically this is all correct, but the photograph seems to be an absurd caricature, since the soles of his shoes take up most of the picture. This photograph of course indicates the inexperience, or feigned inexperience, of the photographer, but optically it is correct. If the brain did not correct the functioning of the eye, we should be coming across such caricatures continually. But psychological correction can lead to error and optical illusion. For instance, the author has himself often been led into grossly miscalculating the size of distant objects. Once a small red traffic sign hanging near overhead tram wires appeared to be a

red flag of enormous dimensions because the sign was erroneously associated with the spire of a distant building at the end of the street. On another occasion for a moment a cat, apparently the size of a cow, seemed to be walking along a distant fence; but in point of fact it was stalking over a roof near the window through which it was observed. Estimates of distance have been as much as 20 times out.

The sun and the moon seem large on the horizon, but small at their zenith. This is another optical illusion for if the sun or moon are photographed on the horizon and at the zenith, they seem to be the same in size in either place. The reason for this is still not quite clear. Perhaps in estimating the luminosity of the sky we tend to accept as

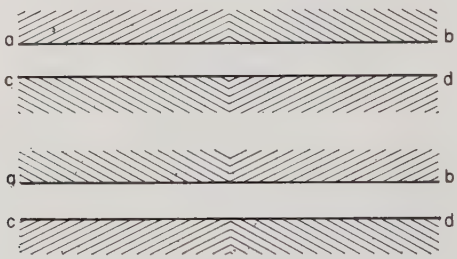


Fig. 41. Optical illusion.

the boundary of the atmosphere that last part of it which sends to our eyes a perceptible scattered light and we relate all objects in the sky to this boundary. At sunrise and sunset the boundaries of the atmosphere in the East or West are most luminous; the limit of the atmosphere which sends us light moves much further away, the sky becomes deeper and we relate the heavenly body to this distant layer. This is the same type of illusion as in the case of the flag and the cat.

Psychological correction also leads to error in the case of plane figures as well as three-dimensional images. For instance, Fig. 41 shows two pairs of parallel lines, and even if the reader concentrates hard the illusion does not disappear. His doubts will only be dispelled if he checks the lines with a ruler.

Figure 42 shows a regular square. The hatching in one corner creates a distinct impression of a crooked square. In Fig. 43 the pattern is made up of discontinuous strictly concentric circles, yet we obtain a complete and lasting impression of a spiral. This can only be

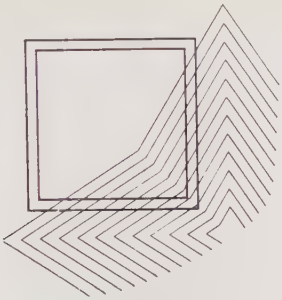


FIG. 42. Optical illusion.

checked by using a pair of compasses. One of the reasons for these optical illusions is that the shading produces an involuntary movement of the eye from line to line. If the drawing is momentarily illuminated by an electric spark, the illusion (at least in some cases) disappears in so far as the eye has no time to move very far during the light of the spark.

Thus, the problem of space and distance is only solved very imperfectly by the human eye and brain.

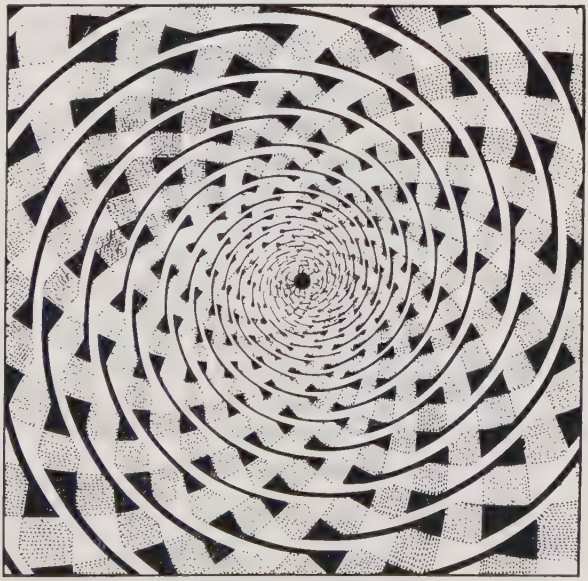


FIG. 43. Optical illusion.

Now consider how the human eye estimates the energy and spectral composition of light. For this it is necessary to describe the structure of the retina in which this estimate is made. The retina is illustrated in cross-section in Fig. 44. The outer layer 1, directly adjacent to the vascular tunic, contains cells which are dyed with a black pigment. We then have the principal elements of visual perception 2, called the

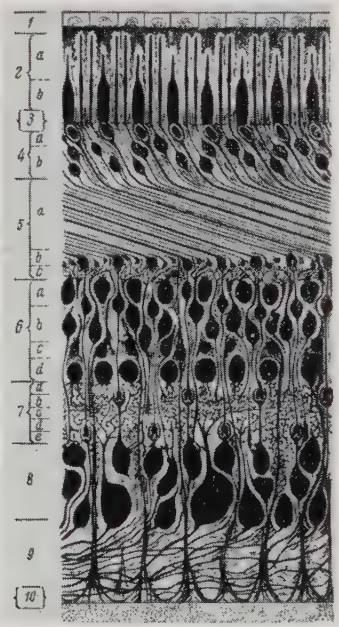


FIG. 44. The retina of the human eye in cross-section.

rods and *cones* according to their external appearance. Layers 3–5 consist of nerve fibres from the rods and cones. Below these layers we have the granular layers, also connected by nerve fibres. Layer 8 contains the ganglion cells, each of which is joined to a nerve fibre in layer 9. Layer 10 is the inner limiting membrane. Each nerve fibre ends in either a cone or a group of rods. The mosaic of these cells on the surface of the retina is far from uniform. The number of rods and cones is very large (about 7 million cones and more than 100 million rods). Figure 45 shows the distribution of cones and rods on

the rear of the eye. The angular distance of the corresponding point of the retina from the "central cavity" (*fovea centralis*) marked along the horizontal axis. These curves are interrupted by the blind spot which we shall discuss presently. It will be seen from this diagram that the cones predominate in the centre of the retina and the rods at the edges. The rods are coloured with red visual purple which rapidly

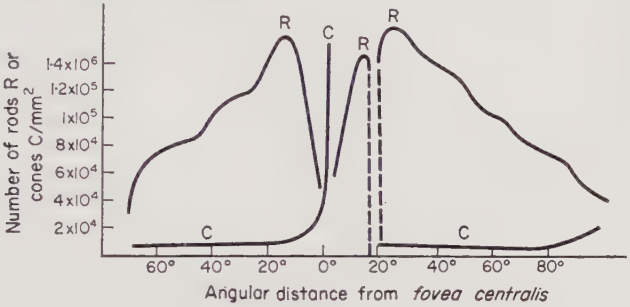


FIG. 45. Distribution of the rods and cones on the retina of the eye according to Oesterberg.

fades under the action of light. The length of the rods is about 0·06 mm and that of the cones is about 0·035 mm. The rods are about 2 μ in diameter and the cones about 6 μ. In the centre of the retina there is a "yellow spot" of oval shape (maximum length 2 mm, minimum 0·8 mm). In the centre of this spot the cones predominate; the rods completely disappear in the "central cavity"; here vision is

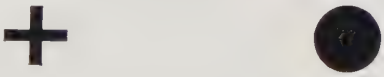


FIG. 46. Mariotte's drawing for finding the blind spot.

clearest and most distinct. Some parts of the retina have neither cones nor rods. In Fig. 46, if we close the left eye and stare with the right at the cross, the black disk on the right will cease to be visible at a distance of about 20 cm from the book, its image coinciding with the blind area of the visual nerve where there are no light-sensitive elements (the blind spot).

Although the optical part of the eye may be simple, the method of perception is not. Not only do we not know the physiological reason for the individual elements of the retina, but we are still in no position

to say, for instance, how the light-sensitive cells have come to be so arranged that a blind spot is produced. We are not dealing with an artificial instrument, but with a live organ which features merits and shortcomings, yet is an integral part of man.

We will consider how the eye estimates the energy of light. It is difficult to isolate this question from that of colour; the eye only receives a visual impression of rays with wavelengths of about 400 to 750 mμ. Ultra-violet rays ranging from 400 to 300 mμ and infra-red rays from 750 to 950 mμ can only be seen if the radiation is comparatively powerful, their visibility in these regions of the spectrum being greatly dependent on the age of the observer and fluctuating widely for different individuals. We will confine ourselves to this range of wavelengths. In the chapter on Light we saw that the energy of sunlight falling each second on each square centimetre of the earth's atmosphere is 0·033 calories. About 40 per cent of this energy belongs to visible rays. The pupil of the eye at its largest does not exceed 0·7 cm^2. It will be seen without difficulty from these figures that the maximum energy of visible sunlight which can penetrate the eye does not exceed 0·01 calories per second. This limit can of course be exceeded thousands of times over by using a mirror or lens to concentrate sunlight, or the light of an electric arc. In nature there are no such mirrors or lenses and factors of this kind have not influenced the evolution of the eye. They can therefore be disregarded. If the energy of 0·01 calories per second were concentrated in the region of green rays with a wavelength of 556 mμ (point of maximum eye sensitivity), the eye would obtain a visual impression equivalent to a lamp of 200 thousand candle power at a distance of 1 metre from the eye. That is the upper limit. On the other hand, the eye is capable of distinguishing the faint light of a dark night when the intensity (energy) is less than a millionth part of a candle. The eye has to adapt itself to this enormous range of light intensities to be of service to living creatures on the earth.

A photographer has three methods of adjusting his camera to a change in brightness. First, he can alter the exposure within wide limits from a thousandth of a second to hours and days. Secondly, he can change the aperture by opening or closing the diaphragm. Finally, the speed of the film can be altered; different film is used to suit particular conditions.

The eye cannot employ the first method because it must take

"instantaneous photographs". But the second method is used. The pupil of the eye is automatically expanded or contracted depending on the brightness of the light. Its maximum diameter is on average about 8 mm, and the minimum about 2 mm. The area of the aperture

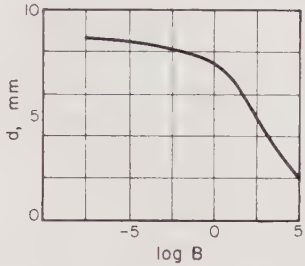


FIG. 47. Variation in the diameter of the pupil of the eye with increasing brightness.

can therefore be varied by a factor of 16. Figure 47 illustrates the variation of the diameter of the aperture with increasing brightness. The logarithm of brightness is marked off along the base and pupil diameter along the vertical axis. Figure 48 illustrates the change in

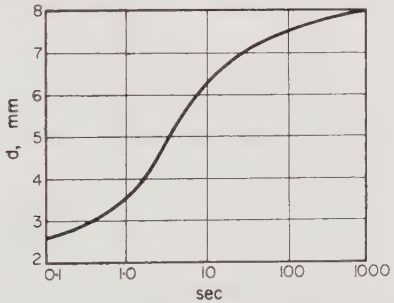


FIG. 48. Variation with time of the diameter of the pupil on going into darkness from a brightly lit room.

pupil diameter *d* on moving from a well-lit building into complete darkness. It will be seen from these diagrams that changes in pupil diameter are inadequate for coping with the changes in brightness with which the eye has to deal. Nature therefore also uses the third, more radical, method in that the sensitivity of the retina is altered. As eyes begin to adapt themselves to darkness, the sensitivity of the retina is

gradually increased. Here the rods and cones behave differently. The sensitivity of the cones only increases a few scores of times compared with daylight sensitivity, but that of the rods gradually (in the course of an hour or more) increases hundreds of thousands of times to a certain limit. The ultimate sensitivity is such that the eye will respond to a stimulation of about 5×10^{-18} calories per second per cm^2 by light of wavelength 500 $m\mu$. But this value varies between different individuals and depends on conditions (small or large light source, intermittent or constant illumination). Furthermore, to attain such high sensitivity, the image of the source must be produced at the edges of the retina where the sensitivity is greatest, and not at its centre. Accordingly, it is necessary to look at the source off-centre.

A wax candle at a distance of 1 *m* from the eye emits about two ten millionths (2×10^{-7}) calories per second per cm^2 in visible rays. To reduce this to 5×10^{-18} calories, it is necessary to move the candle about 125 miles away. In other words, it can be said that the ultimate sensitivity of the eye is equal to the energy of visible light per cm^2 per second from a wax candle 125 miles away from the eye. It is of course assumed that the atmosphere absorbs no light, which is not in fact the case.

It is only in recent years that the amazing adaptability of the eye to changes in illumination has been partly explained. It will be seen from the cross-section of the retina in Fig. 44 that grains of black pigment are present in the outer layer. What is their function? No doubt the pigment weakens the light reaching the rods and cones and tends to protect them from excessive brightness. Yet such protection obviously becomes unnecessary and even dangerous at night. A study of various species of animals (fish and amphibians) has shown that in faint light the black pigment gradually sinks from the upper layer of the retina to the lower layer and thus no longer hinders the ingress of light. The gradual adaptation of the eye to darkness could be fully explained in this way if it were not for the fact that migration of the pigment does not take place in all animals (for example, apes). This matter has still not been settled.

It was said above that the pupil of the eye contracts in bright light, but in some illnesses and after some injections the pupil fails to do so and remains dilated no matter what the degree of illumination. Yet no danger of being blinded by dazzle seems to be present. The light

rays which fall on the edge of the dilated pupil in fairly bright illumination cause approximately 5 times less stimulation of the retina than the rays incident through the centre of the pupil. It is still not known how this is achieved, but in any case there is no doubt that it is largely only the central part of the pupil which is active in bright illumination even if the aperture is fully open; light which passes through the boundary regions of the pupil has only a very slight effect on the retina; on the other hand, in dim light all parts of the pupil are equally active and therefore the light stimulus is greatly increased when the pupil is opened wide in darkness.

FIG. 49. Apparatus for observing the quantum fluctuations of light.

It is natural to suppose that in this case the black pigment which screens the retina in dim light plays a large role. Yet migration of the pigment in the human eye is still not proven.

In the chapter on Light we came across the general law by which light can only be absorbed, or act, in whole quanta. In other words, it is impossible to devise an instrument which will respond to energy less than that of a quantum, because light can only be detected by its effect. Energy of 5×10^{-18} calories per second (for wavelengths of 500 mμ) corresponds to 52 quanta. These 52 quanta are "spread out" over a second. It is therefore clear that instantaneously the eye is capable of perceiving a very small number of quanta, i.e. the eye is almost an *ideal instrument* as regards sensitivity.

The quantum pattern of light can therefore be observed by the human eye. Suppose we are looking at a faint point of light *A* (Fig. 49) which can be dimmed as required. Suppose also that the brightness of this source is reduced to such an extent that only a few quanta come to the eye each second. The quanta cannot follow each other regularly at equal intervals of time; they fly in a disorderly fashion, sometimes in large numbers, sometimes a few at a time. A bright

light also radiates a disorderly stream of quanta, but in this case the number of quanta is tremendous and the percentage random deviation about the mean in practice goes unobserved, just as percentage deviations in the annual birth rate of a city are very small and the population increase can be predicted with great accuracy, whereas the number of births per year in a household of that city varies widely and attempts to forecast additions to the family by this method would undoubtedly be wrong.

Thus, according to the laws of statistics (provided the quantum theory is correct), it is to be expected that wide variations in brightness will occur when a light is dimmed such that only a few quanta reach the eye each second. If the number of quanta reaching the eye is less than that corresponding to the threshold of sensitivity, the eye should perceive no light at all; conversely, if the number of quanta is greater, light will be seen. Consequently, with a gradual reduction in brightness, an instant should occur when the source will change from a constant light to a twinkling light.

However, this experiment cannot be carried out in such a simple form for two reasons. In the first place, we know that the eyeball is extremely mobile so that variations in brightness can be perceived in intense light as well as in faint light. It is therefore necessary to "fix" the eye. This is achieved by placing a brighter (usually red) light at point *O* to one side of point *A*. This brighter red point *O* is fixed by the eye and in this way the image of the red point *O* is produced in the centre of the retina, whilst the image of the point *A* is formed on the side at a constant distance from the centre.

Secondly, the eye is capable of retaining visual impressions; this is of course what happens in the cinema. It is obvious that this property interferes with the perception of rapid variations in intensity, since these variations will merge, mix and lose distinctness for the eye.

However, this difficulty can be overcome by placing a disk, with a single aperture, between the eye and the light source (see Fig. 49). The disk completes one revolution per second and only lets the eye see the light source when the gap comes round (for example, for one tenth of a second). The eye therefore only sees short flashes of light every other second. If the number of quanta in each flash is the same and greater than the threshold, a flash will be seen after every revolution. But if the number of quanta radiated during each passage of the aperture is subject to sharp statistical variations, then obviously

a visible flash will not correspond to every passage of the aperture.

Tests have confirmed this reasoning. In intense light the fixed eye sees a flash every time the gap comes round, but as brightness is gradually reduced misses begin to occur becoming more and more frequent as the brightness is reduced.

By counting the number of misses and flashes it is possible to estimate statistically the average number of quanta emitted in such conditions in one flash. The eye can thus verify the quantum behaviour of light for itself.

It should, however, be pointed out that in this way it is not the sensitivity of the eye as a whole which is determined, but only that of the rods which are responsible for visual excitation. It has been found that the threshold of sensitivity varies widely from two to scores of photon quanta for different individuals. Separate quanta of light have thus become visible in the literal sense.

These experiments are not only of value in optical theory, but they also provide medical research workers with a new method for studying the retina of the eye of the healthy and the sick in the normal state of the eye without surgical interference.

We have mentioned the range of energy with which the eye has to deal. At one extreme the eye can only withstand the direct light of the sun with difficulty, and at the other brightness the threshold of visual stimulation can only be perceived by extreme strain. After looking at the sun for a long period of time, the retina retains an impression of the sun disk and in looking away at a white wall we would see a dark coloured disk on it. This is the exhausted part of the retina at work. The same fatigue can be produced by ordinary lamps if they are too bright. Sometimes, for instance, after a long period of work with an unshaded electric arc, this fatigue can last for hours, and in the extreme case can result in blinding. If we look at the sun or a bright lamp for a long period of time, we can later still see a distinct image of the luminous body even with our eyes closed. Its colour gradually changes, and its intensity gradually fades (*after images*). After images (negative or positive) are a sure sign of abnormal brightness. Sometimes an impression from bright light remains on the retina for almost a day. It can be seen especially clearly at night, or early in the morning, with closed eyes. In this the retina acts like a photographic film. It is still not known what changes take place in the retina to produce this effect. There must be an optimum

brightness which the eye can observe without strain and endure without fatigue.

Figure 50 illustrates the results of an experiment in which a person was made to read a book at a distance of about 10 inches; the degree of illumination was varied and the reader was asked to say how many words he read per minute under the different sources. The degree of illumination is marked off along the base, for example, the figure 40 corresponds to a lamp of 40 candlepower intensity at a distance of one metre from the book. The unit of measurement *lux* represents the illumination obtained from one candle at a distance of one metre.

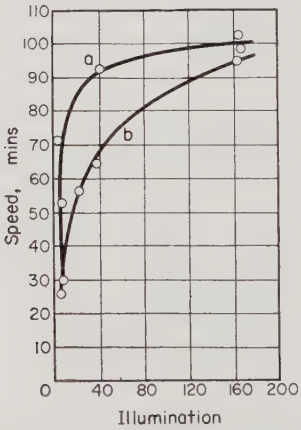


FIG. 50. Reading speed in min (ordinate axis) as a function of illumination in lux.
a – normal eye; *b* – eyestrain.

The number of words read per minute is marked off along the vertical axis. The curve *a* on top corresponds to a normal eye, but the lower curve *b* corresponds to an eye which has been seriously affected by prolonged work in artificial light. We see that at first, reading efficiency increases rapidly with increasing illumination, but at 100 lux this increase ceases. This is a very important fact which has to be taken into account in lighting workshops and homes.

The numerous experiments which have been carried out in the last ten years by lighting engineers and doctors show that the efficiency of various kinds of work is considerably improved if illumination is increased to 300 or even 500 lux. In this case no notable eye fatigue occurs. It is to this limit which our lighting engineers must strive.

In the majority of cases we are still a very long way from this goal. Artificial lighting is not yet being given the great attention which it deserves.

The illumination of the natural environment and the brightness of the images on the retina of the eye vary widely with the season and time of day, the amount of cloud and the objects around us (green fields, snow). It is impossible to deduce an average "optimum" for all living creatures. It is not the same for day animals as for night animals (owls and bats). For the latter the light of our dimmest lamps and candles is unbearable. From the biological point of view, "the optimum illumination" should be the result of the eye's evolutionary adaptation to the average illumination produced on earth by the sun. *The eye is adapted not to the energy of the sun, but to that of the solar light scattered by surrounding bodies.* The variable diaphragm of the pupil, the variation of retina sensitivity, and the existence of an optimum brightness can be regarded as evidence in support of this.

It should also be borne in mind that for eye fatigue it is not so much the total energy entering the eye which is important, as the energy per unit area of the image arriving on the retina. The further a candle is away from the eye, the smaller is its image; but the "specific brightness", i.e. its brightness per unit area of the image, remains constant over a wide range of distances. For example, if we look down a row of city street lamps, the lamps in the distance seem almost as bright as those nearby (the light of the distant lamps is slightly reduced by absorption in the dusty air). It is a different matter if we illuminate a particular surface by the respective lamps; in this case we see that the amount of illumination diminishes very rapidly with increasing distance. A dim light will fatigue the eye badly if stared at, because the image of the filament on the retina is of high "specific brightness". That is why lamps are usually provided with light dispersing hoods and shades. It is because manufacturers of fluorescent lamps were oblivious of this in making them with bright narrow tubes that there have been complaints about the pain in the eye which they produce. This can be obviated simply by placing scattering frosted or opal glass in front of banks of such lamps, or by adopting some system of concealed lighting. It is of course simplest not to look at the lamp direct, but only at the objects which are illuminated.

So far we have been concerned with the absolute estimation of luminous energy by the eye. This estimate is quite qualitative in that

great brightness hurts, and dim lights cause eye-strain, whilst other degrees of brightness are quite acceptable and pleasant; yet we do not feel changes in the size of the pupil, or changes in the sensitivity of the retina; these processes do not reach our conscious mind and it is only they which can be used as an actual estimate of brightness. We hardly notice the minimum of light (the threshold of stimulation) because the visual impression is not retained. It is therefore only the presence of a threshold of visual stimulation which makes it possible

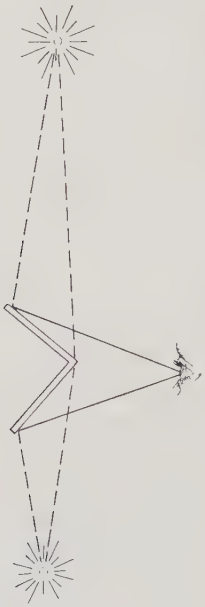


FIG. 51. A photometer.

on occasion to use the eye as an instrument for absolute measurements of the amount of energy in light.

But the eye can *compare* brightness, it can tell that which is brighter from that which is darker. The judgment is again qualitative, but it can be used without difficulty for quantitative estimates. Suppose that two adjacent white surfaces are each illuminated by a separate lamp (Fig. 51). One surface seems darker than the other. There are many ways of reducing the light in measurable amounts (the simplest way is to move the lamp). Let us move one of the lamps so far away such that both surfaces seem to be equally illuminated. It can then be

said that the one lamp is more powerful than the other since its light had to be weakened to give equal illumination. For instance, for a candle on the right and a 16 candle-power lamp on the left, it is necessary to reduce the power of the lamp sixteen times to achieve the same degree of illumination (for instance, by moving it away to four times the distance between the candle and its surface). This method is called photometrical measurement, and the apparatus called *photometers*.

At present there is a large variety of photometers based on the photographic, photo-chemical and photo-electric actions of light. These instruments make it possible to make measurements with great accuracy not only in the visible, but also in the infra-red and ultra-violet regions. But in this book the photometer is only of interest to us insofar as it enables us to detect important properties of the human eye.

How accurately can the eye judge whether two surfaces are illuminated to the same extent? How big must be a change in illumination before it can be detected? Suppose, for instance, that two surfaces are equally illuminated by 1000 candle-power lamps one metre away from each surface; will a difference be seen if the equivalent of one candle is added to one side? Tests show that the answer is no; it is necessary to add the equivalent of about 20 candles for the difference to become noticeable. The ratio of the minimum noticeable increment in illumination to the initial illumination is 20 : 1000, i.e. 2 per cent. Table 2 shows the detectable percentage increment for various intensities (in candle-power) of yellow light with a wavelength of 605 mμ.

TABLE 2

Candle-power	Minimum noticeable increment (%)	Candle-power	Minimum noticeable increment (%)
200,000	4·25	100	2·78
50,000	2·55	50	3·76
20,000	1·83	20	4·60
10,000	1·63	10	6·10
5,000	1·58	5	10·3
2,000	1·80	2	16·7
1,000	1·98	1	21·2
500	2·25	0·5	27·6
200	2·35	0·2	33·2

The initial intensity of 200,000 candle-power roughly corresponds to the illumination of direct sunlight. It is apparent that the eye best

distinguishes the difference in brightness at intensities of 5000 candle-power; the faculty is less pronounced for greater and smaller brightness and larger percentage increments are required, although the increment is almost constant at about 2 per cent for intensity between 20 and 20,000 candle-power.

The ability to distinguish brightness is important for a living creature; it enables it to distinguish one object from another. The range of candle-power where this faculty is most developed (20–20,000 candles) corresponds to those variations in brightness caused by the sun about which we spoke above. Thus, the ability to compare brightness, like its absolute estimation, is adapted to the sun, but not to its direct rays, only to those which are scattered by the atmosphere

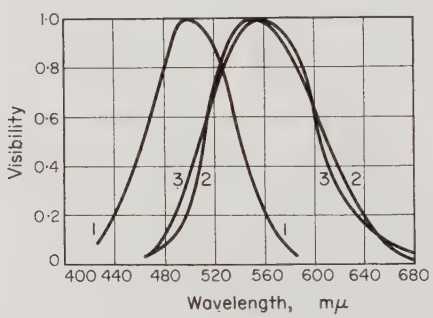


Fig. 52. "Daylight" and "twilight" visibility curves.

and surrounding objects. The "solarity" of the eye, or more accurately, its adaptation to solar light is, however, best evidenced by the way in which it responds to the spectral composition of light. The scale of wavelengths is infinite, passing to infinity at the long wave end, and to infinitesimal wavelengths at the other. The region of visible wavelengths is minute by comparison. Suppose that the eye receives rays of different wavelengths but equal energy. The eye would not see the infra-red rays at all, the red rays would be noticed weakly, the yellow-green rays would seem the brightest of all, the violet hardly perceptible, and the ultra-violet rays almost invisible.

If we take the brightness of the yellow-green rays as unity in order to compare the brightness of the other rays, the energy being equal in all cases (in practice this is not easy to do), a curve of "ray visibility" is obtained (Fig. 52). The wavelength is marked off along the base, and

the visibility along the vertical axis. For considerable brightness, the curves on the right are obtained; curve 2 corresponds to an "average" observer, and curve 3 to an individual at random. We see that the maximum is in the yellow-green part (556 mμ), the curve is steep and almost symmetrical on both sides. Long wave ultra-violet rays of approximately 360 mμ can be seen if their intensity is great. They are violet in colour. Rays with still shorter wavelengths of about 300 mμ can also be seen very faintly. Such rays are strongly absorbed in the crystalline lens of the eye and only very small amounts reach the retina. But, in being absorbed, they produce a blue fluorescence in the eye which is also seen by the retina. If, for example, we look at a source of ultra-violet rays, such as an artificial sun-ray lamp, through a special dark glass which filters off all the visual rays and only transmits the ultra-violet rays, then all the surrounding building will seem to be filled with a bluish mist similar to tobacco smoke. This "smoke" is the fluorescence of the eye, detected by the retina.

Normal eyes only see a small section of the boundless range of rays. What has determined this visible section? It will be recalled (see chapter The Sun) that the solar spectrum on the earth's surface practically ends at about 290 mμ, and that shorter wavelengths are eliminated by the layer of ozone in the atmosphere. Biologically, an eye capable of perceiving rays with wavelengths shorter than 290 mμ would serve no useful purpose. But there is another reason why the eye has not adapted itself to the perception of ultra-violet rays, for it must be protected from them. In the majority of cases short-wave rays destroy organic substances and are capable of killing living organisms. This is the principle of the mercury-arc bactericide lamps in quartz tubes, or more often, in special glass which transmits only short ultra-violet waves. The light of such lamps is used to disinfect hospitals, warehouses, municipal water supplies and so on. This light also produces a good artificial sun-tan, but it can cause blindness if the eyes are subjected to the effect of ultra-violet rays with a wavelength of about 250 mμ for a long period of time.

As we have seen, the retina of the eye itself possesses fairly good sensitivity to rays with wavelengths shorter than 400 mμ (in practice the boundary of the visible spectrum), but it appears that such rays do not reach the retina since the crystalline lens largely absorbs them. The crystalline lens not only produces the image on the retina, but it also serves as a light filter protecting the retina from rays with short

wavelengths beginning at about 400 mμ. By effectively stopping the blue and violet rays, the crystalline lens is instrumental in reducing chromatic aberration, thus making the image more distinct.

These considerations provide a complete biological explanation why light ceases to be visible on the short-wave side (at about 400 mμ in practice).

Now consider the other boundary of visibility at the long-wave end. Why does the eye cease to see in the region of infra-red rays? There are two very good reasons for this. Imagine that the eye was just as sensitive to infra-red rays as it is to green rays. For man, the result would be rather hard to imagine. As we have seen, all heated bodies radiate light; the radiation of all those bodies which are not normally regarded as being heated is concentrated in the infra-red region of the spectrum. The temperature of the human body, and in particular that of the cavity of the eye, is about 37°C. According to the laws of thermal radiation, it can be calculated (see beginning of chapter The Sun) that the radiation maximum of the human body corresponds to the region 9–10μ, and that the energy radiated per cm^2 per second is approximately 0·012 calories. The inner wall of the eye must presumably radiate this energy also; the inside of the eye thus glows with infra-red light. In this case the inner surface of the eye cavity absorbs as much as it radiates. The area of the inside surface of the eye is about 17 cm^2. Multiplying 0·012 by 17, we get 0·2 calories as the total energy of the eye's intrinsic invisible light absorbed by itself. Now imagine for a moment that the invisible infra-red light becomes visible the same as the green. One "green candle" at a distance of one metre emits about 38,000 millionths of a calorie in one second per cm^2; 0·2 calories are equivalent to 5 million candles. The interior of the eye would glow with the intensity of millions of candles. This internal light would outshine the sun and all our surroundings. Man would see only the interior of his eye and nothing more, which is the same thing as being blind.

It is therefore eminently desirable that the eye should not see long-wave infra-red rays.

But why should short-wave infra-red rays not be visible? For instance from 1 to 5μ. The reason appears to be concealed in the very mechanism of vision. Although we do not know for certain, it is safe to assume that vision should begin either where the chemical or the photo-electrical effect of light begins (the latter consists in the

tearing away of electrons from molecules). However, photo-chemical or photo-electric processes can only occur if the energy is not less than a certain minimum amount, otherwise the molecule cannot be torn apart, nor an electron torn away from it.

Several photo-electric processes (e.g. an increase in electrical conductance under the action of light) are now known which extend far into the infra-red region, as regards possible sensitivity, up to 5–6 μ, but the sensitivity in these cases is still extremely small. Photographic plates are likewise insensitive to these regions of waves.

These reasons which depend on the properties of sunlight or the natural effect of light on matter, adequately explain why the eye only sees the narrow band of the spectrum between approximately 0·4 and 0·7 μ.

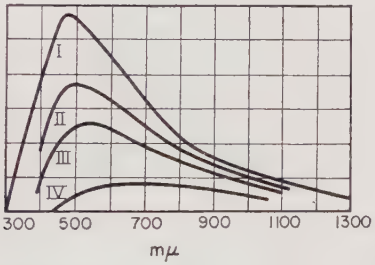


FIG. 53. Distribution of the energy in the solar spectrum at various heights above the horizon.

But there is another very important solar factor which determines this "natural selection" of the visible region. Consider the energy distribution in the spectrum of sunlight. This distribution is far from constant for living creatures on the surface of the earth. It greatly depends on the position of the sun in the sky. At different heights above the horizon, the rays of the sun have to pass through different thicknesses of atmosphere which scatter and absorb these rays differently depending on their wavelength. This was discussed in the chapter The Sun. Figure 53 shows smooth curves (without Fraunhofer lines) for the distribution of the energy in sunlight: I—outside of the atmosphere; II—with the sun directly overhead; III—30° above the horizon; IV—under conditions similar to dawn and sunset, 10° above the horizon. Figure 54 shows the mean annual curve for the distribution of solar energy (upper curve). Presumably

it is this average curve which is most important for the human eye.

It will be seen from the curve that for the "average" sun the energy is distributed almost uniformly throughout the region 450–650 mμ, but that it drops sharply outside these limits. In other words, the visibility curve enclosing the shaded areas *I* in Fig. 54 lie in the most advantageous part of the curve for the distribution of average solar light*.

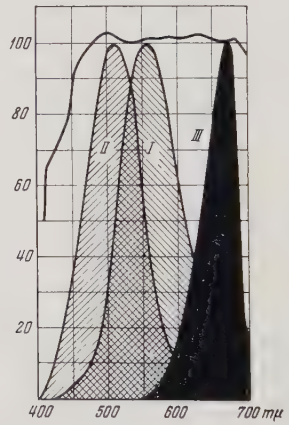


FIG. 54. Mean annual energy distribution curve for the midday sun at middle latitudes (upper curve).
I – daylight visibility curve; *II* – twilight visibility curve; *III* – chlorophyll absorption curve.

If the sole purpose of the eye were to perceive light energy in the most economical way, uniform sensitivity through the interval 0·4–0·7 μ would presumably be the best solution.

But such an approach would be too simplified. Biologically, it is not the absolute sensitivity of the eye to particular light waves which is important, but the ability to *distinguish* illuminated objects from one another. Biologically, to see is not simply to obtain a visual perception but the ability to distinguish all the details of one's environment. The narrowness and sharpness of the visibility curve weakens the effect of chromatic aberration to a considerable extent which improves the

* The spectral sensitivity of the eye coincides with the maximum of the curve for the distribution of solar energy if the spectral curves are expressed in the wavelength scale, but it does not for a frequency scale. Thus, adaptation of the eye to the sun depends not on the stated coincidence, but on the whole set of factors considered in the book.—[*Russian editor*].

definition of the image on the retina of the eye. This is also assisted by the different capability of solid bodies to reflect the various wavelengths. In this respect it is of the utmost importance that the *sharpness of contrast* in brightness and colour of the different objects is greatly enhanced because the visibility curve of the eye is not gently sloping, but instead *has a sharp maximum* and falls away steeply on both sides of the spectrum. It is precisely for this reason that the objects of the surrounding world are so clearly defined.

Once more let us consider Newton's interference rings discussed in the chapter on Light.* It appears that if we were to try and measure the energy reflected from the flat glass and lens by an instrument (a thermal element) which was equally sensitive to all waves, Newton's rings would not be noticed at all. It is only because the visibility curve of the eye is narrow with a sharp maximum that the eye can see these rings clearly. If the eye had a very wide sensitivity curve, we should not see so much about us.

It is to be noted that the visibility curve for day vision almost coincides with the mean curve for the distribution of the energy of sunlight reflected and scattered by green growth. This is of course very beneficial to beings who live amongst vegetation and who to a large extent feed on it.

This is a good example of the successful adaptation of the eye to actual conditions of life on earth and proves the existence of a real relationship between the eye and the sun.*

In very dim light the visibility curve changes quite sharply. Figures 52 and 54 illustrate the visibility curve in conditions of feeble illumination; it is apparent that, relative to the curve for bright illumination, the curve is shifted into the blue region of the spectrum. Physiologists explain this peculiarity of twilight vision in the following terms. The retina of the eye has two types of light-sensitive elements, the cones and the rods. In daylight the cones play the most important part, but their sensitivity is not great; they cease to act when the light is reduced and the rods, with a different sensitivity curve, come into play. From this point of view curve *I* in Fig. 54 corresponds to the "daylight" cones, and curve *II* to the "night" rods.

* The author has observation in white light in mind when the positions of the maxima of some wavelengths coincide with the minima of others; the great selective ability of the eye in distinguishing colours also helps in this case to distinguish the individual maxima, although energy maxima and minima may not exist.—[*Russian editor*].

If the daylight visibility curve is the result of the adaptation of the eye to the scattered light of the sun and to green vegetation, etc., we might suppose that the "night" curve is adapted to the night sky. The light of the night sky (if there is no moon scattering the direct light of the sun) is made up of the light of the stars, the slight scattering of the sun's rays which penetrate into the atmosphere even on the darkest night, and, finally, the natural glow of the sky which amounts to a considerable proportion of the total light. This natural glow of the sky is explained by the radiation of atoms of oxygen and nitrogen in the upper layers of the atmosphere. The spectrum of the night light of the sky is a line spectrum with an especially bright green line having a wavelength of 558 mμ. The luminosity of the sky reaches a maximum about midnight. But certain difficulties arise in trying to relate the "night" visibility curve to the night sky. Adequate measurements have not as yet been made of the overall distribution of the light energy from the stars and from the glow of the sky. According to experiments by Feofilov in 1941, the overall energy distribution of the night sky is equivalent to a black radiator at a temperature of 4000°C, i.e. it is red, and not blue as expected. These measurements cannot, however, be regarded as completely acceptable for they have to be repeated and extended to different parts of the globe for different seasons of the year. In addition, it is again important to emphasize that for the eye in difficult night conditions, more so than during the day, it is not the visual sensation itself which is important, but the ability to distinguish surrounding objects from each other. These matters have as yet hardly been studied. It is impossible to think of the shift of the night visibility curve to the short-wave region as an accident. The whole evolution of life on earth suggests that this shift must be instrumental in increasing the disability of the eye to distinguish at night.

Unlike the eye, which is intended for sight, the leaf of a growing plant must assimilate light energy for chemical changes. This finds its expression in the spectral location of the curve for the photochemical sensitivity of a green plant. In Fig. 54, area *III* represents the main absorption curve of chlorophyll, the green colouring substance of plants. Its maximum is shifted relative to the daylight visibility curve into the region of long waves. How far is this biologically expedient, and why are long waves more beneficial in this case?

Consider once more the fundamental photo-chemical law, discussed

in the chapter on Light, by which it is necessary to absorb one quantum $h\nu$ in order to bring about chemical change in a molecule. This quantum must naturally have sufficient energy to exceed the minimum $h\nu_0$ required for chemical decomposition, for otherwise the reaction does not take place. It therefore follows that chemical changes are unlikely to take place under the action of infra-red rays.

On the other hand, decomposition can be effected by all the absorbed quanta $h\nu$ whose energy is greater than $h\nu_0$. But no matter how great the energy of a quantum, it will only be absorbed by one molecule and the result will be the same as if a quantum with relatively little energy barely exceeding the energy $h\nu_0$ is absorbed. Hence it is clear that photo-chemically quanta with the minimum energy (but greater than $h\nu_0$) are most advantageous for growing plants, i.e. those with the maximum permissible wavelength.

If we now pay attention to the curve for the mean distribution of solar light shown in Fig. 54 (the upper curve), it will be seen that the best position for the chlorophyll curve in the uniform section between 450 and 650 mμ is in the 600–700 mμ region where it actually is.

When a photographer needs to move the maximum of the spectral sensitivity of a plate from one region to another, he colours the light-sensitive layer with various sensitizing dyes, thereby obtaining photographic layers which are specially sensitive to red, yellow or green rays. It can be seen that quite the same thing takes place in nature, the sensitizing agents in this case being the visual purple and chlorophyll.

The shape of the visibility curve is of enormous importance in lighting engineering. Most artificial lighting uses some form of heat radiation (candles, paraffin lamps, electric bulbs and so on); in this radiation only part of the rays are visible and the rest are produced without leaving a trace for the eye to see. If we increase the temperature of a body with a black surface, larger and larger parts of the radiant energy shift from the infra-red into the visible region, and the light source becomes more efficient. But this does not continue indefinitely. At the same time as the temperature is increased, part of the radiant energy moves into the invisible ultra-violet region. Theoretically, it is possible to attain temperatures such that the bulk of the radiant energy passes into the invisible region of ultra-violet and X-rays. This implies that there is an optimum source temperature. What is it?

Table 3 shows the percentage radiant energy emitted as visible light at various temperatures.

TABLE 3

Absolute temperature (°K)	1500	2000	3000	4000	6000	8000	12,000
Energy emitted as visible light (%)	0·0	1·7	14·6	31·8	49·7	47·7	18·6

It is seen that the most advantageous temperature is 6000°K, for which half the total energy is converted into visible light. But this is the temperature of the sun! What is the connexion between the radiation of the sun, a black body and the eye? Has this come about by accident? Now that we have studied light, the sun and the eye, and since there is no doubt that the eye developed as a result of the existence of the sun, in a certain sense for the sun, and under the influence of the sun, it cannot be thought for a moment that this relationship is other than natural and necessary. Both the sun and a glowing black body are seen by the same eye. But the eye has adapted itself to the sun and it is therefore natural for the most perfect solution of the problem to be the production of artificial sources with a spectrum like that of the sun.

How good is the eye at making out the spectral composition of light? So far we have only seen that the eye does not sense the majority of spectral regions at all, and that in the visible region some rays seem brighter than others. If the brightness of red and blue light is made approximately the same we know that the eye distinguishes between the rays unerringly. This implies that besides the magnitude of the sensation, the eye has other means of making out the spectral composition of light. In the solar spectrum, the eye distinguishes seven rainbow colours, and tints which number several hundreds for some individuals. To determine the ability of the eye to distinguish colour, we can compare two adjacent sections of a continuous spectrum and see by how many millimicrons one of the regions can be changed before the difference in colour is detected by the eye. This maximum difference in wavelengths in millimicrons can characterize the ability to distinguish colour in a particular spectral region. Figure 55 shows a curve for the selective capacity of the eye obtained in this way. The wavelength is marked off along

the base, and the maximum permissible differences in wavelengths for which the eye cannot detect a difference in colour are marked off along the vertical axis. The curve is of very complex shape. But yet it does give a basis for our subjective division of the spectrum into rainbow colours. All the minima and maxima of this curve can be regarded as kinds of landmarks between the rainbow colours. Thus, the boundary between violet and blue occurs at about 445 mμ, that between indigo and blue at 460 mμ, that between blue and green at about 500 mμ, that between green and yellow at 540 mμ, and between yellow and orange at 600 mμ. The measurements have not as yet been continued into the red region.

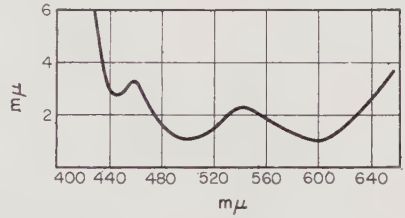


FIG. 55. Curve illustrating the ability of the eye to distinguish the colours of the spectrum.

Only the cones of the retina possess the ability of distinguishing colour; the colours of the spectrum disappear in twilight vision with the rods and all seems grey. Judging from the absence of cones in the retina of the eyes of owls, bats and fish it may be supposed that they are colour blind. To them the world seems like a single-tone photograph, a combination of white and black. The human eye possesses two different types of light-sensitive apparatus. One is like colour photography, which is not very sensitive, and which is used by day, and the other, a single-tone super-sensitive system which is used in twilight or at night.

However, the ability of the eye to distinguish colour cannot rival spectral analysis. If light is arranged spatially in simple rays, the eye can tell the difference in colour quite easily. But it is not difficult to deceive the eye. Any pure spectral colour can be produced by mixing three other simple colours, for example, red, green and violet in different proportions. This is the basis of simple colour photography and technicolor.

Three ordinary photographs are taken of a coloured object through

coloured glass (light filters), for example, red, green and violet. All three negatives have the usual appearance; prints are taken from them on glass (lantern slides). The difference in the three slides is that one of them has been acted upon primarily by red rays, another by green rays and the third by violet rays; the light and shade is therefore distributed differently on all three photographs. The slides are tinted to the colour of the glass through which they have been taken. If the light beams from three projection lanterns are focused on the same part of a screen and we insert the coloured slides, the red, green and violet images are superimposed on each other and the resulting picture of the object on the screen is in all its natural colours. All the rest of the colours are obtained from these three. If, for example, some part of the object being photographed is white, the rays from the object pass into the camera through all three filters. When the shot is later projected on the screen, the red, green and violet are superimposed together and these produce white for the eye. If part of the object were yellow, the rays from it would pass through the red and green filters, but not through the blue; a dark spot which transmits no light will then appear on the blue slide at that point. As a result only the red and green colours are later projected on the screen, which create the impression of yellow for the eye. The technique of modern colour photography is much more complicated than the simple method described here, but the principle is essentially the same for all "additive" methods.*

Generally speaking, only three simple colours are required, in different proportions, to obtain any colour of the spectrum. But these three colours can together produce shades of colour which do not occur in the spectrum, for example, white and purple. If we mix white with some simple colour such as red, the colour still remains red, but it becomes more and more diluted, and its saturation is reduced. Consequently, an infinite variety of reds of different saturation from

* Colour photography produces a correct impression only for the "daylight" eye. In dim light, for example moonlight, colours become quite different, because the curve for twilight vision is shifted into the short-wave region and colour perception disappears in twilight vision. The moon itself seems to be shining with a greenish light, yet the distribution of energy in the spectrum of moonlight is almost the same as that of the sun. If a colour photograph of the countryside by moonlight were to be taken by a high-speed camera using conventional methods, we would probably get an ordinary picture with the usual daylight colouring quite different from the actual picture that presents itself to the eye.

pure red to white can be produced from the simple pure colour. In general any colour can be characterized for the eye by its *brightness*, *colour* and *saturation*. Thus, the variety of colours which can be seen by the human eye is infinitely greater than the number in the visible spectrum. From this point of view, the eye is *very ill-suited as an instrument* for the spectral analysis of light.

In wartime, weapons and trenches, etc. are concealed from the eye of the enemy by camouflaging with the colour of soil and grass, etc. Despite the considerable spectral difference in the light reflected from a camouflaged object and that by the surrounding background, the inquisitive eye can be deceived quite easily; only the spectroscope is in a position to reveal the deception. In the animal kingdom many creatures adapt their colour to suit the environment; many insects have the same green colour as leaves and grass, hares change their fur to match the white snow in winter and the brown earth in summer and so on. It is very remarkable that the colours adopted by animals not only look as if they are the same as their surroundings, but that they also have the same spectral composition. This protection is so perfect that it might be supposed that the eyes of the animals which prey on the camouflaged creatures are perhaps more perfect than our own.

The imperfection of the human eye as a spectroscope is quite understandable. The physicist can only break down complex light into simple rays by spatially expanding the incoming simple rays by a prism or some other instrument.* The spectral composition without spatial separation of the rays can only be estimated very roughly from the special effects of the individual spectral regions on substances. For example, the effect of red rays on a photographic plate is slight, but that of blue rays is strong. It is astonishing how each simple colour

* A simple type of spectroscope can be constructed in the following way. Paint on white paper a rainbow spectrum with colours which only scatter a very narrow range of wavelengths and absorb all the rest. It should be noted that such colours are very difficult to prepare. If we illuminate the rainbow band, e.g. by the light of a mercury lamp, we then see on the paper a rough image of the mercury spectrum. The yellow line of mercury will only be scattered by the yellow section of the painted band, the green by the green, the blue by the blue and so on. The mercury light is resolved into its spectrum. Such a spectroscope is of course only very rough; its advantage is that no slits or prism are required. Instead of a painted spectrum, we can of course produce a set of narrow transparent coloured films which together form the spectrum. The light of this source, transmitted through such a spectral set of films, will produce a rough spectrum on a screen.

produces its own special effect in the eye independently of its energy, even though there is no spatial separation of the rays. In our artificial devices the effect of particular rays can always be imitated by the effect of others by adjusting the energy, provided a continuous spectrum is used. We do not know how such high perfection is achieved in the retina of the human eye. It is assumed that the retina contains three different types of light-sensitive element, each with its own special range of stimulation (Fig. 56). If, for example, red light penetrates the eye, all three elements are affected, they all absorb red light, but to a different extent. The eye is forced to sense this *difference* and the colour red is associated with it. Green light also energizes all three elements, but in different respects than red and so on. The perception of the

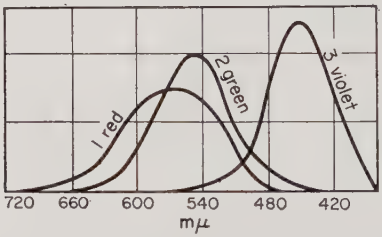


FIG. 56. Curves showing the three fundamental "sensitivities". Ordinate axis – sensitivity in relative units.

total energy in all three elements corresponds to the brightness of the incident light, but the perception of the relationship between the energies of the three elements corresponds to the perception of colour. If there were only one element, it would be pointless to speak of such relationships, and there would be no perception of colour, even though the impression of brightness would remain as before. This idea provides a good explanation of the formation of any colour from three others, colour-blindness (Daltonism and so on), in which the eye loses its ability to perceive hue in certain parts of the spectrum, etc. But as yet this theory has not found an irreproachable confirmation anatomically.

The sensation of colour enormously enhances the value of visual perception. Colour vision provides a rapid means of distinguishing objects and changes in objects. Imagine if man could not detect colour and if we had to judge objects as in an ordinary photograph from the amount of scattered light. In this case two surfaces such as

yellow and green which are photometrically equal would seem to be the same, and many details of the surrounding world would immediately be lost. Moreover, differences in colour are perceived very quickly, whereas it takes a considerable amount of time, and even actual measurements, to establish small differences in brightness (and more so with increasing distance). This is to say nothing of the purely aesthetic value of colour perception.

In view of these great advantages of colour vision, it is very useful to employ colour in regions of the spectrum where it would seem to be excluded by the very nature of things, e.g. in the study of objects by invisible ultra-violet or infra-red rays. This is in fact quite possible under a microscope, as shown by E. M. Brunberg.

Suppose we are taking a photograph of a culture slide under a microscope in ultra-violet light. We take three photomicrographs with three different wavelengths, taking care that they are all on the same scale. Generally speaking, the photographs will be different since some waves are absorbed more than others. We now proceed with the three "black" photographs in exactly the same way as with colour photography (see above). We project them through different colour filters, e.g. red, green and violet, by a lantern on to the same part of a screen and combine the three pictures. We then get a colour photograph of the object taken in invisible rays. In this particular case the photograph is of course artificial. By using differently coloured filters we would get different colour photographs. Such artificial colour photographs of objects in invisible rays are of very great practical value. They provide a rapid means of discovering details in a component which were previously concealed and permit qualitative analysis.

This method can be employed in all forms of photography and need not necessarily be confined to work with a microscope. In this respect the research worker only copies nature in which this astonishing method of visual perception exists.

Our tour of various fields of knowledge has now come to its end. By means mainly of physics, astronomy and biology we finally begin to understand the true nature of the relationship between the eye and the sun.

This relationship is almost the same as that between a camera and the source of light by which the photograph is taken. Of course, in the majority of cases, it is not the light source which is photographed,

but the object illuminated by it, yet the object can only be photographed because it scatters the rays from the source and that is why the apparatus must be adapted to these rays. Its lens must transmit them and produce the correct image of these rays, the photographic plate must possess good sensitivity in the necessary region of the spectrum and the camera cannot do without its diaphragm for different conditions. Similarly, it is necessary to use plates of different sensitivity depending on the amount of light. The human eye, which has adapted itself to the sun as the light source, possesses all these properties. The crystalline lens only transmits to the retina those rays of the sun which are not harmful to the organism and produces a good image in solar wavelengths. The retina of the eye is very sensitive, but for daylight conditions this sensitivity is appreciably reduced artificially, whereas at night it is again increased. The eye has a diaphragm which automatically (depending on the light) varies within wide limits. The spectral sensitivity of the eye occurs at the maximum of the spectral energy curve of the sun.*

All this is the result of the adaptation of the eye to the sun's light on earth.

The human eye cannot be understood without knowing the sun. Yet, knowing the properties of the sun, it would be possible in broad outline to predict theoretically the main features of the eye as they must be.

That is why, in the words of the poet, the eye is akin to the sun.

* See the footnote relating to Newton's rings in this chapter.

"HOT" AND "COLD" LIGHT

Incandescence and Luminescence

Reproduced from the text of Volume IV of
the works of the late
Academician S. I. Vavilov

FOREWORD

In 1941 at the beginning of the Second World War in Ioshkar-Ola I delivered a public lecture on the subject "Cold light". In what were then those testing days for the Fatherland it was useful to disseminate information about luminescence in connexion with war-time blackout. The lecture itself was accompanied by demonstrations. Later in 1942 the text was published by the U.S.S.R. Academy of Sciences.

This particular book contains a part of that lecture. New material and parts of other of my articles have since been added.

Efficient lighting is becoming increasingly important in the national economy, culture and domestic life as each year goes by. Accordingly this book aims to acquaint the public with recent theoretical and practical achievements in lighting techniques and to elaborate on some of the problems which remain to be solved.

A short list of recommended books on luminescence is given.

S. Vavilov

"HOT LIGHT" AND INCANDESCENCE

It is necessary to ponder on the harmless light of decaying wood and glow worms. Then one should write that light and heat are not always related and they are therefore different.

M. V. Lomonosov

An astonishing thing this—the candle.

M. Faraday

Artificial light plays a great and integral part in social development. The use of fire was one of man's great discoveries and as such it marks the beginning of the history of lighting, as well as the origin of fuel and power.

In 1937 one-sixth of all electricity generated in the U.S.S.R. was used for lighting purposes. However, such statistics fail to disclose the real value of artificial lighting.

Without light the eye, this universal, potent and faithful sense organ, is useless. Night deprives man of this organ and his activities are restricted. The role of artificial lighting is to keep man actively alert. Light in fact prolongs his conscious existence and it is in this respect that light is of supreme value. No small wonder therefore that lighting has become a major industry.

All the everyday sources of light, bonfires, candles, matches, oil lamps, electric bulbs and so on, are all alike in that they burn; the sun's rays do likewise; even primitive man was conscious of the sun's great heat. Had it been said, as some did, that the winter sun "illuminates, yet does not warm", the paradox was accepted. The

ancients built up their theory of light on pre-scientific identification of heat and light. In the opinion of many ancient philosophers and physicists, light was rarefied fire. Fire was light in a clotted or condensed form. The same idea persisted for a long time in science. For instance, Newton was puzzled by the transformation of mass into light and vice versa. Wordy dissertations were written on the theme of fire and light. At a comparatively later date, at the end of the eighteenth century, a treatise on fire was produced by the famous French revolutionary and scientist Marat. For these reasons the term "hot light" seems somehow more natural and acceptable than "cold light".

Yet the modern scientist finds either term equally inapt. To him they are as strange as "bright sound" or "loud heat"; "heat", "fire" and "light" are now considered separately. Heat is the energy of the moving particles which make up matter; fire is incandescent gas; light is represented as electromagnetic waves of the same kind as radio waves. Fire may be hot and colourless like the flame of hydrogen and pure alcohol. Heat is related to matter, to the motion of the atoms and molecules of which matter is made. A beam of light contains no atoms or molecules, at least in the ordinary chemical sense whereby they can be accelerated and retarded.

Incontrovertible though they may be, these scientific objections have not curtailed the currency of the terms "hot" and "cold" light in the U.S.S.R. and they are now more in vogue than ever in connexion with the new light sources which are becoming available.

The objections have been ignored because it is easy to say that hot sources produce hot light and cold sources produce cold light. That would be the end of the matter if cold sources did not radiate some heat, and hot sources could not produce cold light.

To go to the heart of the matter, we must consider the various sources of light. Let us begin with the hot.

It is generally realized that the ordinary electric bulb is the outcome of long enquiry and improvement. Yet in principle it is the same as a bonfire. At both ends of the evolutionary scale, a glowing solid substance is used for incandescence, whether the log fire in the hearth, or the tungsten filament in the bulb.

A match is struck and a yellowish flame is seen; its temperature is about 1500°C. With some brands of matches, it is found on closer inspection that the initial yellow flame is the same as that produced

when table salt is introduced into a colourless gas flame. When the match is alight, the bottom of the flame near the stick is pale blue, but the bulk of the flame remains a "warm" orange-yellow due to the incandescence of the soot in the flame. A wax candle produces a flame which is in all respects similar, with a blue portion round the wick; oil-lamps and electric bulbs follow the same pattern. Early electric lamps used carbon filaments; their temperature was about 100 to 200°C higher than that of a candle. The temperature of modern electric bulbs is approximately 2700°C. But as regards the light which such bulbs produce, they are nearer to the log fire than the sun, for its temperature is approximately 6000°C which is far hotter than anything man has yet produced.* The obstacle is the melting and vaporization of metal. In this respect tungsten is the most useful with its melting point at 3660° (absolute temperature) and low vaporization. Attempts to use carbon compounds and metal carbides such as tantalum carbide with higher melting points have failed to produce the desired results.

All these sources of light, candles, matches, lamps, the sun, have a number of features in common. For example, at a particular temperature, their light is brighter if their surface is darker. Whereas a lump of black coal burns brightly, a piece of quartz glass gives off practically no light at the same temperature. But there is a limit to blackness just as there is to whiteness, and at this limit all the incident light is absorbed regardless of its colour. In this sense, an object which absorbs all incident light is said to be an "absolutely black body". By and large, such objects are quite common. For instance, on a bright summer day when all around is bright and shining, the interior of a room looks pitch-black if viewed through an open door or window from a distance, despite the fact that the room may be whitewashed or papered. The light entering the room is completely absorbed owing to the scattering and reflection which takes place there.

In the same way, any material, whether it be coal, iron or white china, can be made into an absolutely black body if it is put in a closed container with a small aperture.

Such an object can be raised to a high temperature, for instance red heat, and held at that temperature. The inside walls radiate light

* This was written before the high temperatures attainable today had been reached.—[*Editorial note*].

which is re-absorbed internally. It is then an absolutely black body and therefore the absorption is by definition maximal, i.e. complete. Since the temperature of the object is held constant, maximum absorption must call forth maximum radiation for otherwise the balance would be disturbed and the object must become hotter or cool down.

Thus, *the radiation of an absolutely black body is maximal as well as its absorption.* Consequently, like the absorption of an absolutely black body, its *radiation must also be independent of the type of material from which it is made.* This conclusion is of immense theoretical importance for it explains the similarity of so many apparently different types of light sources. The log fire, the candle, the electric bulb, the sun, they all have properties akin to those of an absolutely black body. The only real difference is their temperature, 6000°C the sun, 1500°C the match. At low temperatures substances emit invisible infra-red rays; at a certain point they begin to glow dark-red and as their temperature is increased, so they emit orange, yellow and finally white light.

Of course, all objects are not hollow with an aperture and so do not absorb rays of all colours and wavelengths. Objects which completely absorb rays of a certain colour and wavelength may be said to be absolutely black with respect to particular wavelengths. For example, a spirit or gas flame in oxygen is practically colourless in spite of its high temperature. If a little table salt is introduced, the flame turns bright yellow like the initial flame of some brands of matches. In the middle the flame remains transparent; it begins to absorb light in the yellow region of the spectrum; here it becomes absolutely black. That is why it lights up.

For a better illustration consider the following interesting experiment. Certain chemical elements called rare earths, neodymium praesodymium, samarium, etc., display strong spectral absorption bands when introduced into glass or quartz. A thin glass rod or thread can be heated and examined in a spectroscope, it is seen that only several fine lines light up, corresponding to the rare earth absorption; the rest of the spectrum is dark, since the glass itself does not absorb light when heated. The rod only becomes "black" in particular narrow spectral regions.

This explains a number of features of a burning match or candle. The initial bright yellow flash is due to the presence of a small amount of sodium in the head of the match which rapidly burns away. The

pale blue glow around the match stick, or wick, can be attributed to the absence of soot particles in this part of the flame. Here the gas, being absorbing in the blue region of the spectrum, is alight with blue incandescence. As soon as soot particles become present, it is these which then determine the colour of the radiation.

Thus the ordinary warm orange-white light of bonfires and electric bulbs is not a sure sign of a thermal light source. A thermal source can produce a "cold" blue light which is concentrated in narrow bands and lines, and yet still be a thermal source.

The notion that a heat radiation has balance has been explained with reference to an absolutely black body. In the surrounding world, however, bodies are by no means absolutely black. All bodies (unless they are artificially made in the form of cavities with a small aperture) to some extent reflect, scatter and transmit part of the incident light and they cannot therefore be absolutely black. But, even so, they can all be heated and held at a constant temperature. Our own body is warm and under normal conditions its temperature is fairly constant. A balance must therefore exist likewise between the radiation and absorption of light. Let a represent the proportion of incident light which a particular object absorbs; E is the radiation energy of an external absolutely black source; and e represents the energy which the particular object radiates. Owing to the balance between radiation and absorption, it follows for the object in question that

$$e = aE$$

since the absorbed energy is aE; here it must be borne in mind that all the quantities a, e and E refer to a definite light wavelength λ and a definite temperature T. In other words, the ratio of the heat radiation capacity of an object to its absorption capacity (for given λ and T) is equal to the radiation capacity of an absolutely black body for the same λ and T.

Thus, from the most general considerations, i.e. by assuming that objects absorb light to some extent and that they can be held at a constant temperature, it is concluded that any natural object, whether solid, liquid or gaseous, must radiate heat, if it is in thermal equilibrium, at a temperature higher than absolute zero. This radiation will be visible or invisible depending on the degree of heating, but it is always present.

It can be proved without difficulty that the heat radiation of an

absolutely black body for any particular temperature is the maximum possible. In this sense an absolutely black body is the best and most perfect heat radiator. Faraday, in his observation quoted at the beginning of this chapter, had good cause to marvel at the ordinary candle's similarity to an absolutely black body, to say nothing of its practical value.

Yet such "perfection" of candles and electric bulbs is only relative and conditional. All "thermal radiators" (thermal light sources) are extremely uneconomic in the technical sense, for only a very small proportion of the energy which they consume is converted into visible light. For an absolutely black body at 2000°C, only 0·3 per cent of the energy is converted into visible light; at 3000°C the efficiency is raised to 3 per cent. The most efficient temperature is about 6000°C, i.e. the temperature of the sun. This apparently remarkable coincidence is explained by the biological adaptation of the human eye to sunlight in the course of its evolution; light from a thermal source at solar temperature is thus the most economic. But even the efficiency of the most economic thermal source is quite low; only 13 per cent of energy is converted into visible light, all the rest being quite useless for the eye. The efficiency of the most economic modern 100 W electric bulb is only 2–3 per cent.

Two main questions emerge. Why cannot all, or a large part, of the energy imparted to an absolutely black body be transformed into visible light?

The rest of this chapter is devoted to this first question. It has not been easy for physicists to find the answer; it entailed a complete revolution in science and much that was held to be the absolute truth had to be rejected.

If an absolutely black body is held at a constant temperature and it radiates light, then *all* the energy applied to it is continuously converted into radiation. Only a fraction of this radiation is visible, the rest being concentrated mainly in the invisible infra-red region, with lower light oscillation frequencies and longer wavelengths than visible light. The applied energy, being converted into light, is distributed between different waves, creating a continuous heat radiation spectrum. The process takes place in the same way as mechanical or electrical energy is converted into heat. The molecules of matter are set in oscillatory, rotary and forward motion at different velocities, being distributed according to a continuous law by the

random collision of the molecules. The number of molecules in a given volume is finite and therefore, by the elementary rules of statistical analysis, the most probable mean energy of the molecules and the distribution of molecular energy can be ascertained without difficulty.

Until the end of the nineteenth century it was generally held that light was wave motion of the medium filling space. But if that were so, then unlike the particles of matter which are finite in number in a confined space, an infinite possible number of light energy distributions ought to exist with respect to the waves at the equilibrium point of heat radiation.

In fact, however, since the radiation of an absolutely black body for all waves cannot depend on the nature of the substance from which the object is made, no characteristic bands or lines can exist in its spectrum and therefore all the oscillation frequencies from the very low to the very high must be present in a continuous progression. In classical wave theory all frequencies were of equal worth. This implied that an identical infinitesimal portion of energy must on average correspond to each infinitesimal frequency band in equilibrium conditions.

Yet, in passing from the low to the high frequencies, in principle to infinitely high, we meet with an ever larger number of infinitesimal frequency bands each of which has an equal infinitesimal fraction of radiation energy. In other words, in classical theory, under equilibrium conditions radiation energy increases continuously across the spectrum from red to violet. From test results, however, this is not so. For all thermal sources, beginning with an absolutely black body, there is a radiation maximum which, at temperatures below 4000°C, is in the infra-red region of the spectrum and which crosses into the visible yellow and green regions, etc. only at higher temperatures. In the violet region, contrary to classical theory, the energy actually decreases at ordinary temperatures. This inconsistency, based on general considerations of matter and light, was spoken of as the "violet catastrophe" by scientists of the day; it revealed the need for outright rejection of many established views and brought about a complete change in natural science.

From experiments it was found that the distribution of heat energy with respect to the light frequencies is roughly the same as that with respect to the molecules, i.e. it has a distinct maximum. The only

possible explanation (by analogy with the quantum theory) was as follows. Contrary to all previous views and despite the undoubted wave-like nature of light propagation in space, it had to be assumed that the energy was concentrated at particular centres and that light was radiated and absorbed by molecules in whole portions called *quanta*. The energy of a quantum is not constant in magnitude; it is proportional to the frequency ν of light oscillation. But the factor of proportionality h is always the same; though very small it is now known to be exactly $6{\cdot}62 \times 10^{-27}$ erg. sec.

The quantum of energy $h\nu$ is very small for radio waves where the discontinuous pattern of radiation is not in practice noticeable, but

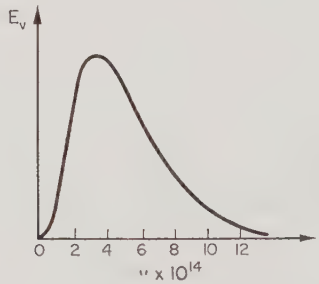


FIG. 1.

it becomes more and more perceptible for visible light and X-rays. Here the quantum structure of light energy is well-defined.

During the half-century which followed the discovery of energy quanta, innumerable fresh proofs of their existence were found. Today this is firmly established truth.

The quantum theory explained all the properties of heat radiation and in particular it permitted analysis of the spectrum of absolutely black radiation at any temperature. Figure 1 shows the calculated energy distribution in the heat radiation spectrum of an absolutely black body at solar temperature 6000° (absolute temperature). The frequency ν of light oscillation is marked off along the base. To convert the frequency ν into wavelengths in centimetres, it is necessary to divide the speed of light 3×10^{10} cm/sec by the frequency ν. The maximum of the curve corresponds to 0·483 micron, i.e. to the blue-green region of the spectrum. Figure 2 illustrates the energy distribution over an extensive range of temperatures by a logarithmic

scale. The logarithms of the wavelengths in centimetres are marked off along the horizontal axis and the logarithms of the quantity proportional to radiation intensity are marked off along the vertical axis. Actual wavelengths are given in microns on the lower scale. It is seen that the maxima of the radiation spectra lie along one straight line. For example, the temperature of the human body

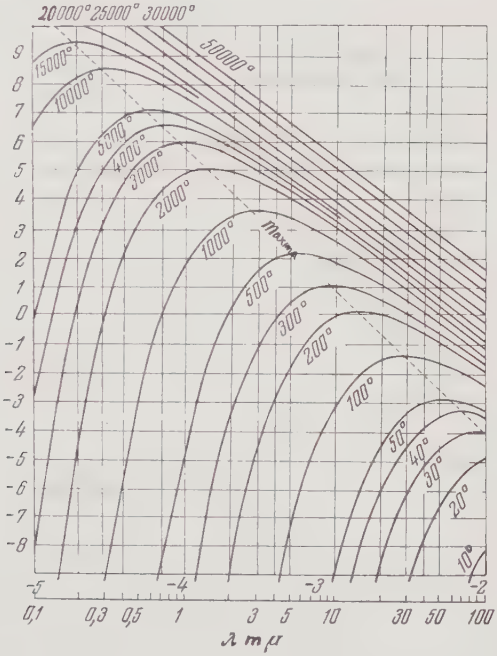


FIG. 2. Distribution of $E\lambda$ to logarithmic scale.
Horizontal axis – log λ (cm); vertical axis – log $2E\lambda$ w/cm².
Actual wavelengths given on lower scale in microns.
Curves at absolute temperatures °K.

(about 37°C, or 310° absolute temperature) corresponds to the radiation maximum of an absolutely black body at about 10 microns in the far invisible infra-red region. At conventional heat source temperatures (3000°C) the maximum corresponds to about 1 micron, i.e. it also is in the invisible infra-red region.

From our foregoing equation it follows that the spectral radiation curves are lower for objects which are not absolutely black, i.e. bodies which do not absorb all incident light. The curves in Fig. 2 represent the "ceiling" values of thermal light sources.

Only after the quantum pattern of light radiation and absorption had been discovered was it possible to explain the low efficiency of thermal light sources. Until then it had been guesswork.

We now know that for an absolutely black body in thermal equilibrium the mean thermal energy of the molecules taking part in the heat exchange must be equivalent to the mean energy of the light quanta which are in energy equilibrium with the molecules, for otherwise the balance would be disturbed.* Here it must be borne in mind that the energy is distributed over the spectrum on both sides of the mean. It will be seen from Figs. 1 and 2 that even in the most advantageous conditions at a temperature close to 6000° (absolute temperature) when the maximum of heat radiation coincides with the maximal spectral sensitivity of the eye, the bulk of the radiation energy lies outside of the maximum, i.e. in the region of reduced visibility or total invisibility. In this is concealed the reason for the inefficiency of thermal light sources. In conditions of equilibrium between radiation and the object, it is impossible to concentrate the total energy in those light quanta which are most desirable for lighting purposes. The bulk of the energy is associated with quanta which are useless in this respect.

The second question is considered in the next chapter. Can a more efficient light source than an absolutely black body be created? It will be seen that this is quite possible; it is only necessary to disturb the equilibrium conditions necessary for establishing balanced heat radiation. This will soon be explained.

* In non-black bodies the relationship is different. Only a part of the molecular thermal energy can take part in the energy exchange with light owing to the incomplete absorption of light.

"COLD LIGHT" AND LUMINESCENCE

"Brighter, brighter shone the light,
Swifter, swifter was their flight
Till they halted where it lay—
There the field was bright as day,
Lit by wondrous brilliant rays—
Cold and smokeless, in their blaze!
Here, Ivan in stark surprise,
Stared and said, 'Why, bless my eyes!
Look—there's light in plenty there—
But no smoke or heat—I swear
Now, this *is* a curious light'."*

P. P. Yershov: "The little hunch-backed horse"

COMPARED with "hot light" the term "cold light" sounds strange and contradictory even after it has been heard many times. Yet the surprise is usually greater when cold light is seen for the first time. This is spontaneously expressed by Ivan in Yershov's verse. The cold blaze is like a fairy-tale wonder.

In fact, the phenomenon of cold light is neither rare nor miraculous; it has been known to man since ancient times and on occasion it has been put to practical use. The writer Eugene Petrov in his "Front diary" describes such an occasion in army lines in 1941 during a frosty winter after lights out. "I observe", he wrote, "many small and large luminous blue grains under foot. It is as though someone has trod on ahead with magic perpetual fire trickling from his knapsack. It takes some time to realize that it is simply bits of rotten wood which a fatigue party has carefully collected in the forest and used

* Translated by Louis Zellikoe.

to lay luminous tracks between the tents. Here such tracks are known as the 'Milky Way'." Though the author reveals the secret of "cold light" in this passage, he still cannot contain himself and, like Ivan, he calls it "magic" to underline his enchantment.

Gradually, however, "cold light" has ceased to be a marvel to behold. Everyone knows of luminous watches, and fluorescent lighting is used in railway stations, the underground and shop displays. Cold light is being used more and more for an increasing range of purposes. Often in the past, and doubtless in the future too, phenomena which have been regarded as rare useless curiosities, have gradually acquired technical importance.

All the facts of cold light prove without a doubt that an absolutely black body is not the most efficient source of light; objects exist which light up in certain coniditons much more brightly than does an absolutely black body in the same spectrum region for the same temperature. However, it is not to be concluded from this that our observations in another chapter were erroneous; the point is that in all cases of cold light to some extent we disturb the equilibrium conditions necessary for establishing balanced heat radiation.

Consider first the various types of cold light. The diversity is much greater than for thermal sources.

Let us begin with the interesting case when "cold light" is produced as a result of a simple mechanical shock. It has been known since pre-historic times that friction or impact can generate heat which is accompanied by light. It is enough to mention pre-historic flint and the sparks issuing from the grinding wheel of the knife-grinder. But the phenomenon in question is profoundly different from these examples. Take a few yellow crystals of uranyl nitrate and set them on an anvil. If the crystals are given a hammer blow in darkness they flash out with a beautiful green light. But if a pinch of uranium filings were struck with the same force, no such light would occur. Even with a very considerable impact, only the reddish glow of the particles would be produced. The heat of the uranium is unimportant in this experiment. When the same experiment is carried out in a heavy frost, it is not surprising to find that the crystals flash out brighter still. There is no doubt that this is an instance of cold light as opposed to hot light.

In connexion with this experiment it is also interesting to find that the fragments of the crystals continue to luminesce, like tracer

bullets, for several hundredths of a second after the hammer blow.

Consider now chemical excitation of light. Take a glass vessel containing a complex solution of triaminophthalic hydrazide with alkali. Hydrogen peroxide and potassium ferricyanide are added to the solution; a chemical reaction takes place which is a remarkable display in that a bright blue light is produced for several minutes. In appropriate conditions a weak blue light will last for hours and even days. The temperature of the vessel during the reaction is low and there is no doubt that this is another example of cold light.

Another interesting example of chemical luminescence is the beautiful green light of a solution of the complex substance "lucigenin" in an alkali solution when hydrogen peroxide is added; this light also persists for hours.

Even though these particular reactions were discovered comparatively recently, chemical luminescence was known to man in ancient times. The light of insects (e.g. glow-worms), pieces of rotten wood, decaying meat and so on are good examples of luminescence resulting from chemical reaction, mainly during oxidation.

With the study of chemical luminescence and the greater attention it is receiving there are high hopes of chemical luminescence becoming a cheap and convenient source of light. Such sources require no electrical power stations, and, like the candle, light is produced by chemical transformation but without the extremely uneconomic process of combustion in the flame. Attempts should be made to improve the lighting potential of chemical reactions; in this connexion it would be desirable to conduct oxidation in atmospheric oxygen and restore the converted substances to their initial state by simple low-cost methods. Chemical luminescence is not as yet past the stage of laboratory experimentation. It is a field of study in which researchers and inventors can usefully concentrate their attention and energy; the object is fully worthy of that.

Light itself is commonly used to excite "cold" light. For this purpose use is normally made of industrially produced mercury arc quartz lamps. In these devices a discharge takes place at a low voltage in mercury vapour. Three main types of lamp are available: low pressure lamps, which form the basis of the luminescent lamps which are discussed in another chapter; high pressure lamps, which are primarily used for experiments with cold light; and extra-high pressure lamps, which concentrate the light with great brightness.

The spectrum of mercury arc lamps is fundamentally a line spectrum. Photographs of the spectra of these three types of lamp are given in Fig. 3. In contrast to thermal sources of light, a considerable proportion of the light energy, especially of the low pressure lamps, is concentrated in the ultra-violet region in the spectrum.

The light of mercury arc lamps is itself an important example of cold light obtained by the use of electrical energy. The temperature of mercury arc lamps, especially the low pressure type, is only a few

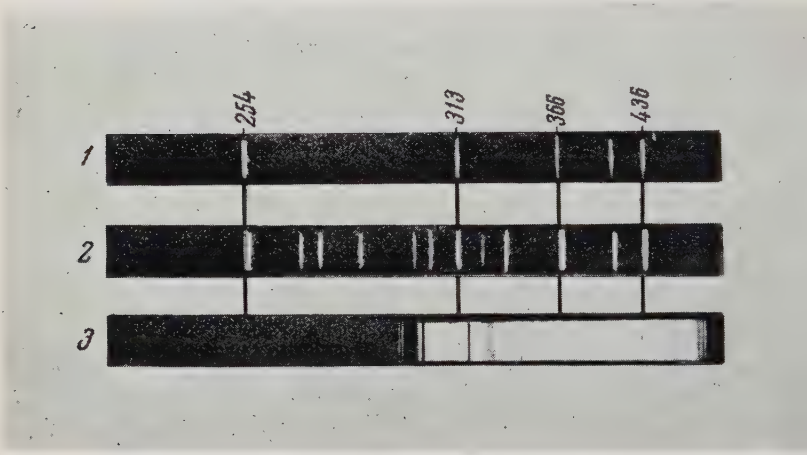


Fig. 3. Spectrum of discharge in mercury vapour.
1– low pressure; *2* – high pressure; *3* – extra-high pressure.
The figures on top denote wavelengths in millimicrons.

score degrees above room temperature, yet they serve as a powerful source of light of long wavelength, i.e. large quanta.

Using glass filters of special, almost black, glass (with a cobalt and nickel content) which stop the visible light and only pass the ultra-violet rays, it is possible to filter out all but the ultra-violet light and illuminate different objects by it.

Many substances themselves light up when absorbing ultra-violet light. In some cases invisible ultra-violet and infra-red light is excited also. If we look steadily at a mercury arc lamp through an ultra-violet filter, the surrounding room seems to be filled with blue tobacco smoke. This is not smoke, but the luminence of the crystalline lens in our own eye under the influence of ultra-violet rays. Our

teeth, skin and fingernails glow in the same way. Figure 4 shows a photograph of a hand taken in ordinary light (left) and one taken in ultra-violet light (right) (the exciting scattered rays were stopped by a light filter while the photograph was taken). On the second photograph a large dark spot is clearly visible on the palm of the hand. This mark is the trace of a burn 30 years previously.

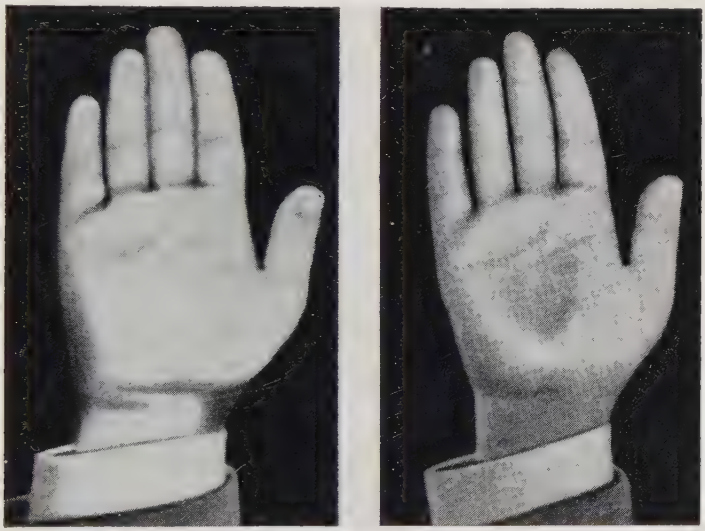


FIG. 4. Photograph of a hand in ordinary light (left) and in fluorescent light (right). The dark spot on the palm of the hand in the right-hand photograph is the result of a burn sustained 30 years previously.

By placing solutions of various organic dyes (rhodamine, fluorescein esculin, etc.) in the path of the ultra-violet light, a bright luminence is obtained in different colours (orange, green, blue, etc). This luminence is not only excited by ultra-violet light. For example, if a solution of rhodamine is illuminated through green glass, the solution gives the same orange light as if exposed to ultra-violet rays. The main advantage of ultra-violet light in experiments of this kind is that it is not directly visible to the eye and so the resulting visible luminence is particularly noticeable.

Another example of light-induced cold light is that of crystals and glass. Crystals of uranyl nitrate and other uranium compounds

emit a bright green light when acted upon by light. It is remarkable that this light is the same whether produced electrically or mechanically (e.g. by a hammer blow). This implies that the nature of the light is in some cases independent of the form of excitation; it depends solely on the chemical nature of the illuminated substance. The cold luminence of uranium glass has long been well known for glass art products; red is obtained from manganese salts and blue from cerium salts.

Most important technically, in recent times, have been special inorganic substances, sometimes called crystal, or mineral, phosphors. They have been known for almost four centuries, but synthetic compositions have only been fully studied for half a century. Thousands of formulae for their manufacture have been discovered. They light up in all possible colours and have a variety of other different properties. They luminesce under the influence of electrical discharges as well as visible and ultra-violet rays. In many cases they emit very bright light.

From the physico-chemical point of view such compounds have quite a special structure. During the past 30 years physicists have obtained incontrovertible proof of their extremely regular crystal structure. In any crystal, for instance table salt and sugar, the atoms are arranged in patterns which form a complete regular crystal lattice. It appears that atoms of extraneous substances penetrate with comparative ease into the heart of the crystal in certain conditions, e.g. if held in the vapours of a particular substance, or if heated in powder form in crucibles at a high temperature. A "foreign" atom, penetrating into the crystal lattice, probably disturbs some of the regular cells of the lattice. A curious condition is formed within the crystal, mid-way between a chemical compound and a solution. In any event the crystal base is a necessary condition for the existence of such phosphors.

Crystals of zinc sulphide into which atoms of copper, silver and other elements are introduced by heating for a long period with other substances in the presence of fusing agents, have attracted special attention.* Crystal phosphors (luminophores) are obtained which become luminous under the action of light or an electron

* Fusing agents are chlorates, sulphates and other salts of alkali and alkaline-earth metals. A fusing agent in a crystal facilitates the introduction of the activator and assists crystallization of the base.

beam and possess a long after-glow, known as their persistence. Whereas the persistence of uranyl nitrate is of the order of several hundredths of a second, that of specially prepared zinc–copper sulphide is 10 hours or more. The colour of the phosphor depends on the nature of the foreign atom. For zinc sulphide the colour can be from red to blue. Sometimes the foreign atom can be a free atom of the same substance as that forming the lattice. For example, pure zinc sulphide in certain heating conditions begins to glow with a blue luminescence. Such a crystal is only pure from a chemical point of view; physically speaking the luminous crystal is always impure; it undoubtedly contains free atoms of zinc which in places break down the regular structure of the lattice and thereby create centres of luminescence.

* * * * *

The foregoing examples provide a good illustration of the notion of "cold" light, even though its many manifestations are by no means thereby exhausted. To understand the physical essence of cold light and its relation to incandescence, it is necessary to consider some of the fundamental properties of cold light. We will concentrate our attention on light-induced luminescence. In this field the laws are clearer and more general and no difficulty arises in applying them to other forms of cold light.

Without fear of contradiction, it can be asserted that "cold" light only appears as a result of the absorption of primary energy, for the fundamental law of nature, the conservation of energy, would otherwise be disturbed. Yet the reverse does not hold; not every light-absorbing substance produces luminescence. For example, ordinary ink, black or red, absorbs light very intensely, but yet it produces no secondary luminescence, whereas solutions of such dyes as fluorescein and rhodamine are superbly luminescent.

As we have seen, heat radiation is quite universal, for nothing can exist at a temperature above absolute zero without producing it. The presence of heat implies radiation. By contrast, cold light is rare; *it is easier to find non-luminescent objects than sources of cold light.* This "specificity" of luminescence is its most important property. It is true of all methods of excitation. But, as yet, science is in no position to explain it.

The second property of cold light is its *persistence.* We have already had occasion to mention the after-glow of uranyl nitrate crystals and

crystal phosphors which continue to luminesce after the excitation has ceased. Persistence varies widely for different substances and conditions, from a millionth of a second for the atoms and molecules of dyes in solutions, to hours and days for crystal phosphors. Intermediate values are found for other substances and conditions. The persistence of luminescence is the decisive factor which distinguishes it from other similar forms of light which are due, for instance, to scattering and reflection, or the propagation of electrons in liquids and translucent solids at velocities greater than the speed of light in these materials (Cherenkov radiation). Superficially these forms of light are similar to luminescence in that they are "cold", i.e. they are independent of temperature, but they are not measurably persistent; they cease as soon as the excitation ceases.

To appreciate the importance of this difference between the two "cold" forms of light, it is useful to have the picture in our mind's eye of that "classical" model of oscillatory light processes in molecules, a simple pendulum suspended on a thread. If this pendulum is swung with a period (cycle) equal to the period of its natural vibration, then when the external acting force is stopped, the pendulum will continue to swing until friction brings it to rest. This model is also representative of luminescence, which continues for a longer or shorter period of time until excitation ceases. Suppose now that the same pendulum is swung with a period different to its natural vibration; we compel the pendulum to perform forced oscillations which are markedly different from its natural period. In this case the pendulum stops almost as soon as the external force is removed. This is the model of light reflection and refraction and the glow produced by electrons of super-light speed in a medium.

In this model the lasting cold light of luminescence corresponds to the *natural* oscillation of the molecules and the other "instantaneous" form of cold light corresponds to the *forced* oscillation.

This necessarily follows from the undoubted fact that light is forever in motion; light cannot be stopped and brought to rest. If light arose and there was no intermediate mechanism between cause and effect, light would inevitably cease (apart from the duration of the period of light oscillation). Conversely, if an intermediate mechanism is present between the causal factor and the radiation, luminence must be protracted and after-glow will persist.

The third remarkable property of luminescence is its *colour*.

In the main the colour tends towards the red end of the spectrum, away from the excitation colour. A good test is provided by taking pure sulphuric acid which, like all "pure" liquids, almost always contains some small organic foreign matter from the air. When excited by light this foreign matter luminesces. Suppose we concentrate the light of a mercury arc lamp on a flask of sulphuric acid. If the light is passed through a filter which only transmits the ultraviolet rays, blue luminescence is produced. If the filter is changed for one which is blue, the luminescence has a green cast. Finally, using a green filter, the luminescence becomes very faint and acquires a red-brown hue. Thus, as the colour of the exciting light approaches the red end of the spectrum, the colour of the cold light is shifted further backwards in the same direction. This is known as Stokes' law.

It is a law which has been obeyed in every case which has ever been studied. By virtue of the quantum theory of light, Stokes' law can be generalized to any form of light excitation. As we have seen, light energy is concentrated in quanta $h\nu$, or hc/λ, where c is the velocity of light. To obtain such a quantum, according to the law of energy conservation, it is necessary for the energy of the agent directly causing the quantum hc/λ, for example, an electron or colliding molecule, to be at least equal to hc/λ. Therefore the "mean wavelength" of luminescence caused by an agent with energy E is given by the inequality

$$\lambda \geqq \frac{hc}{E}$$

Light excitation and Stokes' law are ordinarily a special case of this more general expression which is suitable for other types of excitation. In fact, if the luminescence is excited by light consisting of quanta with energy

$$E = h\nu_0 = \frac{hc}{\lambda_0}$$

then, substituting hc/λ_0 for E, the optical Stokes' law becomes

$$\lambda \geqq \lambda_0$$

These arguments reveal the quantum character of Stokes' law and generalize it. Just as with incandescence, the quantum theory is needed to explain the fundamental properties of cold light.

* * * * *

The term "cold light" has been used throughout on a par with the scientific expression "luminescence". Now that the fundamental properties of this form of light have been established, we are in a position to be more precise in our terminology. Naturally it is the idea and not the words which is important.

To be precise, we cannot relate hot or cold radiation simply to the temperature of the source. A heated body producing thermal radiation can still be a source of cold light. The gas flame and table salt was a case in point. The matter can only be resolved by observing the light of the sodium lines in the flame, measuring the absorption of the flame and comparing the radiation with that of a black body in the same spectral region at the same temperature. On the other hand, phosphorus, which gives a typical cold light, necessarily also emits thermal radiation corresponding to its temperature. Furthermore, the scattered light from powdered zinc sulphide and its curious luminosity are both identically cold, yet they are profoundly different in their nature.

To avoid confusion and uncertainty, science has coined the word *fluorescence*. Fluorescence is defined as the *excess of light from a body above the heat radiation of the same body in a given spectral region at a given temperature, provided that the excess has a finite duration of fluorescence, i.e. that it does not cease immediately after the causal factor is removed.*

This is a clear definition which distinguishes fluorescence from incandescence, light scatter and other similar processes by a measurable characteristic. In the following we therefore dispense with the picturesque, vague and even erroneous notion of cold light and confine ourselves to the term fluorescence as defined above. It is to be hoped that this new and more apt term will come to be used in the future in the same way as radio, electricity and many other special terms have become current.

* * * * *

The achievements of science in comprehending the nature of light and the structure of matter make it possible to understand the main properties of fluorescence.

The quantum structure of light has already been discussed and it has been seen how the quantum theory explains the heat radiation balance and Stokes' fundamental law of fluorescence.

However, the quantum laws are not only applicable to light; they

also determine the structure of matter. The intrinsic energy acquired by an atom or molecule is of a stepped discontinuous nature. Energy cannot be imparted to a molecule in any amount; only one of the values in a discrete series can be imparted. The discontinuous character of atomic and molecular spectra is associated with this fact (see, for instance, the mercury spectra in Fig. 3).

If a quantum of light is absorbed, an atom or molecule is said to change from the normal to the excited state. The molecule remains in this state for a period of time which varies very widely from millionths of a second to practically complete stability. It is in fact this time which we measure in experiments on the duration of fluorescence.

In simple cases it is immaterial whether the molecule is excited by light, the impact of other particles, or some other means. If under the action of an exciter an atom changes to the excited state, it afterwards radiates light quanta regardless of the type of excitation. It will be recalled that the crystals of uranyl nitrate produce the same light whether excited by hammer blows, ultra-violet rays or electrons.

These conclusions are quite general and they are equally valid for equilibrium incandescence as well as fluorescence.

The elementary phenomena which occur in thermal light sources are essentially the same as those taking place during fluorescence. In either case molecules are excited by the absorption of light or by their inter-collisions. In thermal light sources the excitation is due to the random thermal motion of the particles and their radiation is equally random. On the other hand, in fluorescence, the transmutation of energy into light takes place in an orderly manner without waste on other forms of energy which produce no visible light. Excitation by heat, e.g., by ultra-violet light, is like the action of a jostling crowd of men running in all directions compared with the same men on military parade. The number of men is the same, their energy is the same, but in one case all is chaos, whereas in the other everything is orderly, harmonious and purposeful. The heat produced by conventional light sources is not a universal characteristic of lighting, it is only an expression of its imperfection.

Heat from a light source is a superfluous, irrational and uneconomic waste of energy. The absence of heat from fluorescent sources is a sign of their economic supremacy.

Our definition of fluorescence clearly distinguishes the principal

difference between fluorescence and incandescence. *In a fluorescent medium some of the energy imparted to the molecules does not enter into the general heat distribution.* The proportion can be very large. Such energy is as it were barred from communication with the rest of the medium.

Insulation of the excitation energy from the heat distribution in fluorescent bodies is only a special case of insulation in matter. A good illustration is the enormous energy latent in the nucleus of the radium atom which, carefully insulated from exchange with the external medium, is released only after the lapse of enormous intervals of time measured in many hundreds of years. An excited potentially fluorescent molecule can retain energy which is scores and hundreds of times greater than the mean thermal energy of its particles.

The ability of a molecule to insulate the energy of excitation in this way depends on particle structure. This is the explanation for the relative rareness and specificity of fluorescence. It is common knowledge, for instance, that the regions "responsible" for the fluorescence in the atoms of rare earths are well protected by an outer electron shell from external effects, which explains the fluorescent capability of these substances. However, in the majority of cases, the structural features on which the fluorescent capability of different molecules or crystal phosphors depends has still to be established. This is the top priority problem in the theory of fluorescence

Owing to the insulation of the excitation energy from the heat energy in a fluorescent body, the object's store of energy is, as it were, kept in non-communicating upstairs and downstairs compartments. On the bottom floor, the thermal floor, energy is exchanged and distributed, owing to which equilibrium is established. On the top floor the processes of exchange, if they occur, are of a special resonant nature which leads to no equilibrium, only to the journeying of the excitation energy in quantum form from one molecule to another. In each fluorescent body we meet with the rather astonishing state of affairs in which thermal equilibrium exists side by side with absence of equilibrium. The distribution of energy to different "levels" is far from instantaneous. The excess energy received by a molecule in the absorption of light or during electron bombardment first appears to produce a general perturbation. Some of the excitation energy is transferred to the medium and enters into the equili-

brium radiation balance. Such leakage corresponds to the shift of the fluorescence spectrum towards the red region. Yet the reverse process is also possible, i.e. part of the thermal equilibrium energy of individual molecules can change into excitation energy. In either event, however, the store of heat is not on average reduced; in other words, a body is unable to cool down during fluorescence since on the "bottom floor" the laws of thermodynamics prevail and thermal energy cannot be converted into the "harmonious" energy of fluorescence without expenditure of corresponding work.

According to the laws of thermodynamics the change of thermal energy into excitation energy must be compensated by a reciprocal

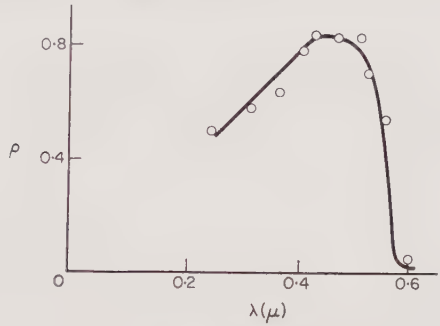


FIG. 5.

change of excitation energy into heat. Actually, in that region of the spectrum where the wavelength of the exciting light becomes greater than the mean wave of fluorescence (i.e. the region where Stokes' law is upset), the fluorescence output, i.e. the ratio of the radiated energy to that which is absorbed, begins to decrease and this decrease is greater the further the exciting light passes into the region where Stokes' law is contradicted. Figure 5 illustrates the variation of the fluorescent output of a fluorescein dye solution as a function of the wavelength of the exciting light. The steep drop at the long-wave end corresponds to the transition into the "anti-Stokes" region. This behaviour is typical of all fluorescent substances which have so far been studied. It can be regarded as a generalization and refinement of Stokes' law.

* * * * *

The main idea of this discussion is to make one point clear. If all the energy absorbed by any substance were completely distributed between its particles and ultimately entered into the heat balance, the only possible sources of light would be incandescent sources. The absolutely black body would be the limit of perfection. Fortunately this is not so. The structure of many substances is such that a large proportion of the energy which they absorb of appropriate quality (high speed electrons, ultra-violet rays and so on) does not enter into the heat distribution; it is emitted directly in the form of light without using an extremely uneconomic thermal link. New vistas of technical progress are thus opened up. These are considered in the next chapter.

THE SUPREMACY OF FLUORESCENCE

"We cannot wait for favours from nature; to take them from her is our task".

I. V. Michurin

"If man depends on Nature, then she depends on him. Nature made him and he remakes nature".

A. France

Man has evolved on earth under the thermal radiation of the Sun. As the outcome of a long struggle for existence, the human eye, man's most important and delicate sense organ, has adapted itself to the solar spectrum. Only recently has he sought to reproduce sunlight artificially as a substitute for the Sun at night. Fire and fuel, wood, coal and oil, are free accessible gifts of nature. The history of lighting down the ages has therefore been the history of thermal light sources. In this respect the line of least resistance has been followed. The temperature of those light sources is very low compared with the Sun and their light is redder and weaker.

The radiation spectrum of incandescent bodies can of course be "rectified" qualitatively and approximated in composition to the solar spectrum by heating, provided goggles with blue glasses are used for instance. "Daylight" incandescent lamps in blue glass have already been produced on this system. But the improvement has been obtained at still greater cost. The already very low efficiency of incandescent lamps has been reduced still further from 2–3 to 1 per cent. Such lamps are another example of wasted energy.

The electric bulb was undoubtedly a great advance in lighting.

However, it was only progressive in that electrical energy was converted into light and not heat. The success of the electrical bulb was bound up with the construction of electrical power stations. This success was dearly bought, the precious chemical energy of coal and oil being concerted into heat. Only about 20 per cent of the energy content of the fuel is transmitted along the power lines and reaches the consumer. Since the efficiency of electric bulbs is only 2–3 per cent, it is seen that *only a small fraction of one per cent* of the original energy of the coal and oil is converted into light. Over 99 per cent of the fuel is squandered.

As we have seen, this wasteful method of producing light is not the only feasible system. We can and must avoid the easy way out; the so-called natural way of producing light is not acceptable; it is necessary to stop following the line of least resistance. One of the most important technical problems in many fields of engineering is that of finding methods of converting one type of energy into another without employing the thermal mechanism. In lighting the method has already been found in the form of fluorescence which opens up new lines of development in the conversion of energy (mechanical, electrical, chemical or light) into visible light.

Fluorescence is not at all a new discovery. It was studied by scientists in the seventeenth century. Galileo was one of the first. What has held back the revolution in lighting? As we have seen, two conditions must be fulfilled for fluorescent radiation to occur: 1. the substance must be capable of fluorescence; it is known that many bodies cannot or are not able to luminesce; 2. a molecule must receive exciting energy in the form of a light quantum at a frequency not less than the fluorescence frequency, or in the form of a particle, such as an electron, with equivalent energy.

In the fluorescence of decaying fish described by Aristotle the fluorescent particles were complex organic molecules and the necessary energy arose from the chemical reaction of oxidation. The eighteenth-century Russian scientist and philosopher Lomonosov studied the green light of mercury vapours by shaking an empty glass tube containing a small quantity of liquid mercury. In Lomonosov's experiments the fluorescent substance was the same as that which we are about to discuss, mercury vapour; the excitation was produced by the moving charged particles due to electrification by friction between the liquid mercury and the glass walls of the tube.

Neither Aristotle, nor Lomonosov, could have produced a practicable fluorescent light source, since they, like the rest of humanity until the second half of the last century, had no suitable means of converting thermal, mechanical or chemical energy into electricity. The efficiency of electrical machines in the seventeenth and eighteenth centuries was very low, the steam engine had only just been invented and chemical supply sources were in their infancy. Only modern electrical engineering with its generators and transformers made possible the full-valued harmonious forms of energy which are required for the excitation of fluorescence (high-speed electrons and ultra-violet rays).

Fluorescent lamps were not practicable before the end of the nineteenth century. Their present form is the outcome of a long search which will eventually force nature to yield to man's will as regards rational lighting.

Many attempts have been made in the last half century to design and utilize fluorescent lamps. The streets of Moscow, Leningrad and other large towns display lighting advertisements in red, green and blue. These are high-voltage discharge lamps in which mainly the gas neon, or mercury vapour, is made to glow.

Such lamps have existed for several decades and they are economic in the sense that a large proportion of the electrical energy is converted into light. Their economy is, however, more than offset by a number of inconveniences (the use of high voltage, awkward shape, spectral composition).

Sodium vapour lamps are a better proposition in that a low voltage supply can be used. They produce a bright yellow light like that in a spirit flame when table salt is added; in some cases over 50 per cent efficiency has been achieved compared with 2–3 per cent for ordinary electric bulbs.

Sodium lamps have not been widely used owing to their unsatisfactory spectral composition. In the bright light of sodium vapour, objects become the same in colour, which is not at all agreeable to the eye. Sodium lamps have therefore been a special-purpose form of lighting.

Mercury arc lamps are also imperfect. Their efficiency is no more than 10 per cent, being much less than that of sodium lamps. The whitish green light which they produce is very disagreeable. Attempts to light Gorkii Street in Moscow 15 years ago by such lamps brought forth a storm of protest from the Muscovites.

Many propositions have been put forward, but none of the luminous gas and vapour lamps has solved the lighting problem.

The solution was found by combining mercury arc lamps with the solid crystal phosphors which were discussed in another chapter.

Such compounds convert one kind of light into a different kind. For instance, they convert ultra-violet light into green light, and green light into orange light, i.e. like all fluorescent substances, they act as *light transformers*. Such transformer compounds can obviously be of immense value in lighting engineering. With their aid invisible, dangerous, and for lighting purposes useless, ultra-violet light can be converted into visible light; homogeneous light can be transformed into wide spectral bands of the most diverse form and, more particularly, into a replica of the energy distribution of daylight. Sometimes the transformation ratio is in this respect very large.

The practical value of fluorescent light-transformers was not hard to perceive. A century ago master glassblowers producing discharge lamps for demonstration purposes sometimes made them from fluorescent uranium glass; the glow of the gas discharge was bright and relatively efficient.

Twenty years ago in the U.S.S.R. and abroad systematic experiments were initiated with a view to utilizing the invisible ultra-violet spectral region of different mercury-arc, argon and other lamps by means of fluorescent films, glasses and crystal phosphors. The practical and theoretical aspects of this problem have already been resolved.

The biggest proportion of all contemporary fluorescent lamps are low-pressure mercury arc lamps with the addition of argon. They are in the form of cylindrical tubes 15 to 50 mm in diameter and 80 to 15 cm in length. Tubes containing a few milligrams of mercury are filled with argon at a pressure of several millimetres of mercury. In use their temperature is at most about 15°C, the pressure of the mercury vapour here being insignificant, amounting only to about a hundredth of a millimetre of mercury. The argon content is necessary for best use of electrical energy in the discharge, but the light produced by the discharge is mainly determined by the mercury. The electrode at each end of the tube consists of a tungsten wire coil activated by strontium and barium oxide. When the lamp is switched "on" the electrodes heat up and the heater current is automatically connected by a special device (a relay) consisting of a small discharge tube filled with neon. One of the electrodes is made from a bi-metal

plate whose position is very sensitive to temperature. After automatic interruption of the ignition current, the temperature of the electrodes is maintained by the arc discharge. To limit and stabilize the circuit, a "choke" is incorporated which consists of turns of insulated wire wound on a core made from iron rods. For a 20 W lamp the current is 0·35 amps and the voltage 62 V in a 110 V network.

If the discharge takes place in pure glass, a faint blue light is produced; the main fluorescent radiation is concentrated in the invisible ultra-violet region of the spectrum, primarily in two spectral lines with wavelengths of 0·2537 and 0·1849 microns. To convert this invisible radiation into visible light, a thin coating of a "light transformer" compound is applied to the inside wall (a crystal phosphor which lights up in response to these particular spectral lines). The desired colour (green, blue, yellow, etc.) can be obtained by using the appropriate crystal phosphor powder. However, substances which reproduce "daylight" are of most interest and importance. The word "daylight" is not at all precise in meaning. The illumination in natural conditions varies greatly with the time of day, the season of the year and the weather. Some luminous compounds reproduce average daylight for a cloudy sky; they are known as "daylight" compositions. Another common type of compound is said to be "white"; it is, as they say, slightly "darker", i.e. its tint is closer to that of an ordinary electric bulb. Various radiation spectra can be obtained by using different compounds and mixtures of compounds. In the U.S.S.R. compounds have been produced which light up by themselves, but mixtures in lamps which radiate light with a spectral composition very close to that of daylight are still to come.

Consider now the economics of the new fluorescent sources of light. For lamp efficiency to be maximum, it would seem that all the electrical energy applied to the lamp should be converted into visible light and this visible light should be green with a wavelength of about 0·55 micron, since this corresponds to the maximum sensitivity of the human eye in daylight conditions. It is, however, clear that no such lamp could be "ideal" if for no other reason than that which limits the use of sodium lamps. Such lamps would be monochromatic and they would turn the multi-coloured surroundings to which the eye is accustomed into a drab contrast of light and shade in green tones. Even so, the realization of such a lamp would contradict the quantum laws of light. As we have seen, in a fluorescent lamp the fluorescence

of the crystal phosphors is excited by ultra-violet spectral lines of $\lambda = 0{\cdot}2537$ and $0{\cdot}1849$ microns. In our "ideal" lamp the radiation would have to be concentrated in the spectral green line with $\lambda = 0{\cdot}55$ microns. But since only one green quantum can arise from one ultra-violet quantum (at least in ordinary conditions), for visible radiation only a fraction $0{\cdot}23/0{\cdot}55 = 0{\cdot}45$ of the excitation of the first ultra-violet line is used, and only $0{\cdot}18/0{\cdot}55 = 0{\cdot}33$ of the second.

It is therefore impossible to achieve maximum economy of electrical energy in fluorescent lamps for normal lighting purposes (i.e. in "daylight" and "white" lamps). If we take the mean energy distribution of the solar spectrum in the visible limits and the curve for the spectral sensitivity of the eye in daytime, we can calculate the maximum conceivable efficiency of such lighting. It is no more than 40 per cent. Thus the quality of day whiteness can only be bought at the cost of an approximately 60 per cent energy loss.

Furthermore, the loss due to the large difference in the wavelength of the exciting light and the mean wavelength of daylight radiation reaches at least 50 per cent.

Altogether, an ideal fluorescent tube of the type under consideration converts about 20 per cent of electrical energy into visible light. The energy loss of the mass-produced article is greater, which brings the efficiency down to about 10 per cent. In contrast with the 2–3 per cent efficiency of the ordinary electric bulb, the existing fluorescent lamps are already 3–4 times more economical.

The new lamps are not without many drawbacks. It is necessary to increase their efficiency still further by improving the phosphors, and perhaps using a different substance in place of mercury. Lamps in the form of long tubes are not convenient in shape. It is, however, quite possible to produce them in the form of tubular rings, this being the best shape for desk lamps and domestic lighting. A big drawback is that they cease to ignite at low temperatures owing to the reduced pressure of the mercury vapour, but this will doubtless be overcome. The fluorescence life of the crystal phosphors currently used in such lamps is very short; lamps with an alternating current supply exhibit intermittent illumination with a frequency of one hundredth of a second. For this reason rapidly moving objects are seen with a typical striped appearance. This can largely be overcome by employing a special system of lamps in which the maximum light of one lamp coincides with the minimum of another. There are, however,

grounds to suppose that fluorescent compounds can be produced with sufficient persistence to eliminate this disadvantage.

Despite these drawbacks, it can be said without exaggeration that modern fluorescent lamps mark the beginning of a new chapter in the history of lighting engineering.

* * * * *

The higher efficiency of fluorescent sources is not the only practical advantage of fluorescence. All the distinctive characteristics of fluorescence serve different useful purposes. It has been seen that the process of light transformation was fundamental to the invention of fluorescent lighting, i.e. the conversion of ultra-violet radiation into visible light by fluorescent powders. Crystal phosphors, aptly called luminophores, have acquired very great importance as light transformers. The discovery of X-rays in 1895 was only made possible because these hitherto unknown rays with very short wavelengths were partially converted into visible light on striking various fluorescent substances. Today the technique of medical investigation by hard X-rays is on the whole based on light transformation.

The last half century has also witnessed the growth of a new and important specialization in the form of fluorescence identification techniques and analysis, which are also based on light transformation.

The incidence of ultra-violet light on different objects in many cases stimulates visible radiation of a colour which depends on the chemical composition of the object. By using mercury-arc lamps and black filters which only transmit ultra-violet light, objects in conditions of almost complete darkness can be made to emit visible radiation. In such conditions full use is made of the enormous sensitivity of the human eye which can adapt itself to darkness and see very small details and small amounts of foreign matter. Fluorescence analysis is widely used in chemistry, medicine, the fishing industry, metal-working, mineralogy, forensic medicine, criminal investigation and so forth. The hand burn shown in the photograph of Fig. 4 is a good illustration of fluorescence analysis.

Stokes' law indicates that light rays can only be converted into rays with longer wavelengths. Can anything be done in the reverse direction. i.e. can long-wave rays such as infra-red rays be converted into visible light?

The knowledge and ingenuity of man frequently finds roundabout ways of overcoming obstacles like Stokes' law without invalidating them. Two ways of exciting visible light by infra-red rays have already been found. In electronic night-vision apparatus the invisible infra-red picture strikes a photo-cell which is sensitive to infra-red rays. Electrons are then emitted from the photo-cell, and their energy is increased by an additional electrical field. A fluorescent screen is placed near the photo-cell. The electrons strike the screen and produce the required visible light. In this case Stokes' law is circumvented in that the energy of the infra-red quantum, which is converted into electron energy, is augmented by a portion of electrical energy so that the total energy of the process suffices to excite visible light.

The other "trick" is a purely lighting technique. Certain crystal phosphors only light up faintly after excitation and they remain almost dark. It was known for a long time that some of these substances will light up much more quickly if they are heated or illuminated by infra-red rays after excitation by ultra-violet or visible light. This suggested a way of obtaining a visible flash of light by infra-red rays which at first glance seems contrary to Stokes' law. It will be readily appreciated that this is not in fact so. The infra-red quantum plays the role, not of an exciter, but of a trigger for the large charge previously obtained from the ultra-violet rays. Luminous substances have recently been made from alkaline earth compounds using two rare earth activators (cerium and samarium, or cerium and europium). These compounds are far superior to any other fluorescent substances for the purpose in question. They can hold the stored energy for weeks with practically no dissipation at normal temperature. When illuminated by infra-red rays with wavelengths up to two microns they produce a bright green or red glow which vanishes again almost as soon as the infra-red illumination ceases. In this way fluorescence provides a means of transforming part of the invisible infra-red spectrum into visible light. Soviet physicists and astronomers have thereby been enabled to detect new stars and nebulae in the firmament which could not formerly be seen by the eye or photographed. Fluorescence has greatly widened the spectral sensitivity of the eye by extending its range from the narrow 0·4–0·7 micron band to that between 2 micron and to wavelengths as short as we please.

Besides light transformation, special importance also attaches to the conversion of electrical energy in the form of electron beams into visible light. Modern television systems are based on the fact that an electron beam rapidly scanning a fluorescent screen leaves behind a luminous trace with varying degrees of persistence. By fluorescence the energy of electrical signals is converted into visible pictures. In radar apparatus, which is of immense value in modern warfare, spots and lines of light are produced on a fluorescent screen. Fluorescence is thus a staunch bridge between light and electricity in the most diverse practical applications.

* * * * *

As we have seen, fluorescence is only possible because the excitation energy does not spread throughout the medium; it does not enter into the heat balance of the object. This fact determines the most important practical advantage of solid fluorescent substances. Excitation is highly *localized*. In gases and liquids such localization naturally does not take place, owing to the low viscosity of the medium and the rapid motion of the particles of matter. By virtue of the property of localization a picture of an object can easily be produced on a fluorescent screen by a photographic lens. That is why fluorescence is used in television and radar. It is also the reason why fluorescence is so useful in camouflage and air-raid precautions.

Obvious boons are often frustrated by war. The benefit of artificial lighting in towns and on the railways becomes a threat to safety during night raids by enemy aircraft. But the complete switching off of all artificial light at night is a much too primitive, expensive and irrational method of taking cover from the eye of hostile aircraft. Such a method brings movement and transport in towns almost to a complete standstill; rail traffic is disrupted, especially at marshalling yards, and industrial work is slowed down, particularly on outdoor sites. It is best to provide illumination which allows more or less free movement on the ground without being visible to high-flying enemy aircraft.

This can be partially achieved in many cases and in this respect fluorescence makes a great contribution. Conventional thermal sources of light have two disadvantages in black-out conditions: 1. the sources themselves, e.g. electric bulbs, are very bright and they can easily be seen from a great height if they are not appropriately

screened; 2. such lamps emit light in all directions, they illuminate everything regardless of need. For instance, in a conventionally-lit engineering workshop the ceiling, walls and the floor are all illuminated and as a result light would stream from the windows unless blacked out. Yet, for normal duties, it is only essential for the personnel to see the measuring instruments and the main control levers. In the ordinary way, however, nothing more can be done than blot out the windows. This solution makes the presence of windows completely pointless.

A way of escape from such blind alleys is indicated by a study of fluorescence. We replace the ordinary incandescent lamp by a mercury arc lamp with a hood which only transmits ultra-violet light. The essential parts of the premises, such as the dials of the measuring devices, the levers and the switches are then coated with fluorescent compositions. All that is essential within the building is visible yet very little light, which cannot in any case be seen from an aircraft, penetrates the unmasked unpainted windows.

Luminous paints, the main constituent of which is usually zinc sulphide activated by copper, are applied to pointers and signs and used to outline doorways in towns, on trains, at the docks, on warships and aircraft and so on. The property of localization of fluorescence is utilized throughout in all these respects.

Fluorescence has long been used in the peace-time theatre and it is gradually being accepted in art. Many formerly complex theatrical problems were solved without any difficulty as soon as the use of invisible ultra-violet light and luminous compositions was learned. Spectacles of opera, ballet and pantomime can be contrived quite simply. For example, it is easy to show a dancer executing a complex and difficult dance on one leg simply by covering the other leg with a non-fluorescent material. All other parts of the dancer can then be seen except for his one leg. Fluorescence also enhances the staging of such productions as "Orpheus in the Underworld", "Sadko" and "The Little Hunch-backed Horse". The beauty and phantasy of the scene with Fire-Birds' feather presents no difficulty whatsoever.

Luminous compounds also have good prospects in art. Conventional paintings which have existed in various forms since ancient times are based on the scattering of external light, daylight or artificial light, from a thermal source by a colour image. This sets limits to the scope of artistic expression. Above all, all known paints feature wide

spectral bands in scattering of white light; it is almost impossible for a painter to produce pure saturated tones. Only if the paints are applied to glass, and the picture is looked at against the light (e.g. stained glass windows), can sufficiently saturated tones be produced. In conventional paintings the range of brightness is very limited. In fact the pure whites scatter no more than 95–97 per cent of the incident light; the rest is absorbed. Black paint reflects about 5 per cent of the incident light and the rest is absorbed. Thus the maximum brightness of coloured areas on a picture can vary between 5 and 95 per cent, i.e. variation by a factor of 20 can occur. It is sufficient to call to mind sunbeams in a woodland glade with alternate sunlight and deep shade under the trees, or the sky with a setting sun or a rising moon. Such scenes are quite beyond the reach of conventional art techniques.

The scope is altogether different for the artist who uses fluorescent paints which light up under ultra-violet light. Here pure saturated tones are perfectly attainable, here degrees of brightness can be achieved corresponding to the range in nature. In fluorescent art, landscapes with the sun and the moon and suchlike subjects are perfectly realistic. Striking successes in this direction have been made by Soviet artists.

* * * * *

As we have seen, the excitation energy received by a fluorescent body is prevented from taking part in the overall energy exchange which leads to thermal equilibrium. This is the explanation for the localization (insulation) of excitation in solid fluorescent bodies. However, localization is related to the *finite persistence* of fluorescence after the excitation has ceased.

The persistence of fluorescence is widely used for a variety of purposes in engineering. As early as the beginning of the nineteenth century, before the discovery of photography in its present form, it was proposed to obtain pictures of objects by projecting them through a lens on to fluorescent layers which possessed a high degree of persistence. Such pictures could have persisted for several hours before fading and disappearing. Even at that time the pictures or silhouettes could have been drawn and fixed on tracing paper.

The persistence of fluorescence assumes considerable importance

in war-time. Large surfaces are coated with luminous compositions in air-raid shelters and wherever there is a danger of sudden interruption of electric lighting as a result of air bombardment or other causes. Useful personal sources of light can be obtained for several hours by exciting small surfaces about the size of a postcard with a bright active light such as that produced by burning magnesium tape. This luminous postcard can be kept in a pocket when no light is required since the light of fluorescence is "cold " and it does not

FIG. 6. Night-light made from fluorescent plastic (photograph taken several hours after being switched off).

burn the suit. It can be fastened to the coat to avoid collisions with other passers-by on the streets during the black-out. The same postcard can also be used as a backing for writing in darkness if the writing paper is sufficiently transparent.

A cardboard or tin cone coated on the inside with a long-persistence luminous composition is a good substitute for torchlight since a person can carry such a cone hanging from a cord and it will adequately illuminate a circle round his feet.

A lampshade made from plastic with a copper-activated zinc sulphide content will continue to act as a useful night-light after the lamp has been switched off (Fig. 6). The light will last throughout

the night until morning provided the appropriate luminous substance is used. Any translucent fabric can be used in place of the plastic if it is coated with a suitable lacquer containing an emulsion of some pulverized luminous substance.

It is very important to find fluorescent substances which combine great persistence with brightness. This is necessary for the excitation during daylight hours to last out the next night until dawn. When such substances have been produced, very interesting prospects will be opened up for railways and roads without electric lighting and for lighting in sparsely populated regions.

In the future it will probably be simple and economical to use fluorescent paint to light up railway sleepers and road-side posts and trees over great distances. As yet it is not possible to produce paint with the necessary qualities for this purpose, although the solution of the problem undoubtedly comes nearer each day. In recent years luminous compositions have been obtained in the U.S.S.R. which are ten times brighter than any hitherto known similar substances even after a lapse of 8 hours from excitation. This success is insufficient to overcome the night problem completely, but it is near to it. Here we have before us one of the fascinating lighting applications of fluorescence.

The property of persistence is also of important value in technical apparatus in which electron energy is converted into light. In television the electron beam, rapidly scanning the fluorescent screen, leaves the picture behind it. However, if the object is moving, it is necessary for the fluorescent spot excited by the electrons to die away as quickly as possible to leave a clear space for the next signal. Persistence of the picture is assured by virtue of the inertia of visual perception. Luminous substances which fade out rapidly after electron excitation are therefore used for the screens of domestic television sets. Ordinary crystal phosphors are eminently suited to this purpose. On the other hand, in radar and certain special technical devices, it is desirable for the electron beam recordings to persist on the screen for a longer period of time. Special substances have been evolved for this purpose with great electron-induced persistence. Alternatively, "two-layer" screens may be used. The lower layer of such a screen produces a rapidly dying violet, or even ultra-violet, light in response to excitation by electrons. This light penetrates into the other layer on top and excites a green luminous colour. The

excitation of the second screen is induced by light and it therefore has great persistence. In this way two-layer screens provide persistent recordings of electron beams.

* * * * *

Most persons who have seen the luminence of crystal phosphors wonder whether a phosphor can be produced which is perpetually luminous. Naturally, this is quite impossible with conventional substances because of the law of the conservation of energy. Even an ideal phosphor only gives back what it has received; the root of the trouble is that phosphors can only assimilate a limited amount of energy. The number of centres which are capable of excitation is limited and once all have been excited, any further incident light is useless for it passes straight through.

There is as yet only one way of obtaining "permanent phosphors", i.e. phosphors which luminesce with an even faint light for years, if not forever. The method is to add a very small amount of radium or some other radioactive substance to the luminous compounds. Radium is an outstanding example of self-disintegrating atoms. It takes 1700 years for half of an ordinary lump of radium to decay into other elements. In the course of decay energy is liberated which is concentrated in what are known as alpha, beta and gamma rays. The alpha rays are the nuclei of the helium atoms, the beta rays are electrons, and the gamma rays are light rays with extremely short wavelengths, shorter than X-rays. Gamma rays are hardly absorbed in matter and their light-inducing effect is therefore of little consequence. The main luminescence is caused by the alpha rays. The alpha particles, meeting with crystals of zinc sulphide, are absorbed over a very short distance and enormous energy is released of which at least a small percentage is converted into visible light. One nucleus of the helium atom causes what is essentially an explosion; the effect is visible in the form of a bright flash of luminescence (scintillation).

If the zinc suphide did not gradually deteriorate under the action of the radium radiation, a radium-bearing luminous crystal phosphor would last in practically its original form for centuries and even thousands of years. But in fact the zinc sulphide does deteriorate and after the second year the luminescence is notably reduced.

The luminence life of permanent phosphors depends on the amount of radium which is added. But there is a limit to how far we can go

in this direction from purely economic considerations. Radium is a very rare and expensive element; one gramme of radium costs over a million roubles. About 10 milligrammes of radium are required per one kilogramme of phosphor to obtain an acceptable, though faint, luminence. The cost of a kilogramme of "permanent phosphor" thus comes to over 10,000 roubles (i.e., £440 sterling or U.S. $1200 per lb), whereas the same phosphor without radium costs 200–300 roubles (i.e. about £11 sterling or U.S. $30 per lb).

Yet the larger the radium content of a particular phosphor, the sooner it fades. Nevertheless, "permanent" luminous substances have been made for decades and are used for luminous dials particularly on military equipment. In general it may be said that the bulk of the radium procured on earth is used for permanent phosphors (luminous paints). These are used to coat the faces of watches and dials.

Is it not possible to use another substance in place of radium which is less scarce and costly? It is to be hoped that the development of nuclear physics in the not too far distant future will lead to methods of obtaining artificial radioactive substances in place of radium. It may be mentioned that "permanent" luminous compounds could have been discovered, at least in principle, a hundred years ago, if researchers, chemists and physicists had carefully examined in darkness the crystals of such uranium compounds as uranyl nitrate and, more particularly, the complex salt, potassium uranyl sulphate. They would have seen that these crystals luminesce in darkness. The reason is concealed in the slow decomposition of the uranium atoms. There is naturally a very long way to go from these faint sources of light, and even from more powerful modern compositions, before they become a practicable means of lighting. But we are entering an era of actual mastery over nuclear energy and it is to be hoped that sooner or later nuclear energy will be used for lighting purposes, and not only indirectly through electrical power stations which use nuclear energy as fuel, but directly as well in systems like present-day "permanent" phosphors.

Great is the role of science and engineering in our country. Soviet men know that such inventions and discoveries as railway communication, aviation, the internal combustion engine, telephone, radio, germ control, the cinema and photography stand for the development of human society. That which our folk-tales and folk-songs

foresaw and ascribed to gods and magicians (conversations over thousands of miles, flights at lightning speed on magic-carpets, preservation of the appearance, movements and voices of those who have passed on), all this has become commonplace like the cart and the samovar. If you please, it is even the other way round, for in many parts of our Fatherland the cart and the samovar have become much rarer than the aeroplane and the electric kettle.

There is no need to be endowed with any special gift of vision to foresee a not far distant time when "cold light" will become an ordinary household convenience like the electric bulb.

"Cold light" is the only rational solution of the lighting problem, it is the escape from the rut of thermal light sources in which nature keeps us, it is mastery over nature, her re-making. "Cold light" is part and parcel of the cultural life of future communist society. It is our duty to bring nearer the day when "cold light" will be in widespread use.

LIST OF RECOMMENDED BOOKS ON LUMINESCENCE

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12. *Scientific Literature on Luminescence.* Bibliography 1935–1946, (Nauchnaya literatura po voprosam lyuminestsentsii. Bibliografiya 1935–1946 gg). Izv. Akad. Nauk SSSR (1948). (A detailed list of scientific articles and books dealing with the theory and practice of luminescence published abroad and in the U.S.S.R. in the period specified, 334 pages).

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* Added by the Translator.

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The two articles featured in this book were written by the late eminent Soviet scientist S.I.Vavilov. He was a president of the U.S.S.R. Academy of Sciences and received a Stalin Prize first class in 1951 for this book. In the first article he outlines the history of the study of light and discusses the nature of light, the properties of sunlight, the structure of the human eye and how the eye percieves light. The second article considers the "cold" light of luminescence. The purpose of this book is to acquaint the reader with theoretical and practical achievements in lighting techniques and it elaborates on some of the problems which remain to be solved. Both articles are standard popular science works which have never failed to attract the interest of a very large public. The whole book is devoted to physics and is written with the authority that one naturally associates with a man of such eminence, yet it is readily comprehensible by the layman. Former Academician S.I.Vavilov's book is an excellent introduction to the subject of illumination, and it will be very useful for senior form school pupils and for those at technical colleges. As mentioned, the book will also be an acquisition to all libraries catering for the wide interests of the public.

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